COLORADO FOREST CARBON INVENTORY

Forest Ecosystem and Harvested Wood Product Carbon Accounting Framework Through 2019

Anthony G. Vorster[1], Christopher Tsz Hin Choi[1], Ashley M. Prentice[2], Nicholas Young[1], Olaf Kuegler[3], Maria Gaetani[2*], Amanda West Fordham[2,1], Ethan Bucholz[2]

1 Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523
2 Colorado State Forest Service, Colorado State University, Fort Collins, CO 80523
3 USDA Forest Service, Pacific Northwest Research Station, Portland, OR 97205
* Maria Gaetani was a former Research Associate with the Colorado State Forest Service at the time of this work

December 11, 2024

WARNER COLLEGE OF NATURAL RESOURCES
COLORADO STATE UNIVERSITY

COLORADO STATE FOREST SERVICE
COLORADO STATE UNIVERSITY

NREL
NATURAL RESOURCE ECOLOGY LABORATORY

ACKNOWLEDGMENTS

The authors sincerely thank everyone who contributed to the development of this report. We are especially grateful for the invaluable advice, resources and feedback received from those involved with implementing statewide carbon accounting frameworks in California, Oregon and Washington. The pioneering work completed in these states provided us with a tremendous foundation. Our appreciation goes to Nadia Tase of the California Department of Forestry and Fire Protection and Jeremy Groom of Groom Analytics for contributing significant time, expertise and engagement throughout the development of this report.

We extend special thanks to those at the USDA Forest Service Rocky Mountain Research Station Forest Inventory and Analysis (FIA) program, including Sara Goeking, Kristen Pelz, Erin Berryman, Karin Kralicek and Erich Kyle Dodson. We are appreciative of support from Glenn Christensen of the USDA Forest Service Pacific Northwest Research Station. Thanks to those who manage FIA's comprehensive database. Additionally, we are grateful to the Colorado State Forest Service (CSFS) FIA program including David Hanley, Andrew Clements, Dan Ek, Nathan Rausch and the dedicated field workers who tirelessly navigate Colorado's forests to collect the data critical to this report and forest carbon accounting framework.

We thank our colleagues within the CSFS, Tim Reader and Kurt Mackes, Keith Stockmann of the USDA Forest Service and Todd Morgan of the University of Montana Bureau of Business and Economic Research for providing expert advice and support on harvested wood products in Colorado. We thank Paul Evangelista for his review and valuable feedback. We are also grateful to Brian Sathe, Kristy Burnett, Field Peterson, Dan West, Phoebe Bauer and James Lucero of the CSFS for their contributions. Additionally, our thanks extend to Angela Boag from Colorado Parks and Wildlife and Molly Pitts from the National Wild Turkey Federation for their specialized expertise and support.

We would like to acknowledge the state legislature of Colorado for recognizing the importance of this topic and providing the necessary funding to complete this work.

COVER: The Noku Craigs are a rocky outcropping in the Colorado State Forest, which is managed by the Colorado State Forest Service. ***Credit: CSFS***

BACK COVER: The Deer Creek GNA project thinned overgrown forest to help protect critical infrastructure that provides clean drinking water to 1.8 million people downstream. ***Credit: CSFS***

Recommended citation: Vorster, A. G., Choi, C. T. H., Prentice, A. M., Young, N., Kuegler, O., Gaetani, M., West Fordham, A., & Bucholz, E. (2024). Colorado forest carbon inventory: Forest ecosystem and harvested wood product carbon accounting framework through 2019. Colorado State Forest Service Report. Fort Collins, CO: Colorado State Forest Service.

Contact information: Anthony Vorster (*anthony.vorster@colstate.edu*) and Ashley Prentice (*ashley.prentice@colostate.edu*)

ACRONYM LIST

BLM – Bureau of Land Management

CO_2e – carbon dioxide equivalent

CDPHE – Colorado Department of Public Health and Environment

COGHGI – Colorado Greenhouse Gas Inventory

CSFS – Colorado State Forest Service

DBH – diameter at breast height

DNR – Department of Natural Resources

EPA – Environmental Protection Agency

FIA – Forest Inventory Analysis

GHG – greenhouse gas

GRM – growth, removals, and mortality

ha – hectare

HB – House Bill

HWP – harvested wood product

IPCC – Intergovernmental Panel on Climate Change

Kha – kilo hectare

LULUCF – Land Use, Land-Use Change and Forestry

NGHGI – U.S. National Greenhouse Gas Inventory

MBF – thousand board feet

MCF – thousand cubic feet

Mg – megagram, equivalent to a metric ton

MMT – million metric tons

NFS – National Forest System

NGHGI – National Greenhouse Gas Inventory

NLCD – National Land Cover Database

NRI – National Resources Inventory

NREL – Natural Resource Ecology Laboratory

NSVB – National Scale Volume and Biomass

NWL – Natural and Working Lands

PIU – products in use

SB – Senate Bill

SIT – State Inventory Tool

SWDS – Solid Waste Disposal Sites

Tg – teragram

TMT – thousand metric tons

WWPA – Western Wood Products Association

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

In response to state legislation to address knowledge gaps about Colorado's forest carbon, this report presents a forest carbon accounting framework for Colorado that will be updated periodically. This framework provides an in-depth analysis of carbon stocks in both the forest ecosystem and harvested wood products (HWP). The forest ecosystem model utilized Forest Inventory and Analysis (FIA) plots measured from 2002 to 2019 to estimate Colorado's forest carbon stocks and changes in carbon stocks (fluxes). Stocks were calculated using FIA plots measured from 2010 to 2019. We used FIA plots first measured between 2002 and 2009 and then re-measured between 2012 and 2019 to determine how carbon stocks changed from forest growth, mortality and removal. This method tracked changes in individual trees over time for areas that remained forested at both the first and second measurement but excludes urban forests. We summarized stocks and fluxes of forest ecosystem carbon by pool (aboveground live tree, aboveground standing dead tree, belowground live and standing dead tree [i.e., roots], down woody material, aboveground and belowground understory vegetation, litter and soil), disturbance, land ownership, forest type, county, National Forest and Colorado State Forest Service (CSFS) area. The harvested wood product model tracks carbon in timber products as it moves between products in use and solid waste disposal sites, and as it is emitted to the atmosphere with or without energy capture. We gathered information from a variety of sources to create a time series of harvest volumes across ownerships from 1954 to 2019 to inform this model.

Colorado's 22.8 million acres (9.2 million ha) of forests held 1,552.6 ± 23.5 TgC for plots measured between 2010 and 2019. The state's forests were a net source of carbon, with forested land remaining forested emitting 0.9 TgC yr^{-1} based on plots first measured between 2002 and 2009 and re-measured from 2012 to 2019. Most of the state's forest carbon resided in the aboveground live (20% of stocks) and soil pools (59%). Widespread tree mortality during the reporting period (2002 to 2019) resulted in the aboveground live carbon stocks having the greatest losses (-3.8 ± 0.5 TgC yr^{-1}). Mortality removed 8.5 ± 0.6 TgC yr^{-1} from the aboveground live pool, which far outpaced growth (5.0 ± 0.1 TgC yr^{-1}) and removals (0.4 ± 0.1 TgC yr^{-1}) and was a major contributor to Colorado's forests acting as a carbon source during this time. This high mortality-driven reduction in the aboveground and belowground live pools led to gains in the aboveground and belowground dead and down woody material pools. Insects and diseases impacted far more area (2,547.9 ± 138.2 thousand ha) in Colorado than all other disturbances combined, accounting for 85% of the total area disturbed and 64% of the disturbance carbon losses.

National Forest System (NFS) lands comprised the greatest forest area and carbon stock followed in descending order by private, other federal and state and local government. Forests on NFS lands had the greatest loss in carbon (-0.608 TgC yr^{-1}), followed by private (-0.183 TgC yr^{-1}), state and local government (-0.046 TgC yr^{-1}) and other federal lands (-0.030 TgC yr^{-1}). Most FIA forest type groups were net sources of carbon during this period, although the ponderosa pine group (0.100 ± 0.080 TgC yr^{-1}) and woodland hardwoods (0.073 ± 0.062 TgC yr^{-1}) were weak carbon sinks. The aspen/birch group experienced the greatest net carbon loss (-0.586 ± 0.222 TgC yr^{-1}). Nearly half of Colorado's forest carbon was stored in two forest type groups: the fir/spruce/mountain hemlock (29% of total stocks; 454.0 ± 26.7 TgC) and the pinyon/juniper groups (20%; 313.7 ± 14.9 TgC). We found the carbon stocks, fluxes and carbon densities of each forest type group to vary substantially by the four CSFS areas, with some forest type groups acting as carbon sinks in some regions, but sources in others. The western CSFS areas contained the most forest area and stocks and experienced the greatest forest carbon losses.

The harvested wood products records we compiled show that a total of 15.3 TgC (9.9 million MBF), or an average of 0.2 TgC yr^{-1} (149,677 MBF yr^{-1}), was harvested across all ownerships in Colorado from 1954 to 2019. Harvests were highest before 1979 and dropped by roughly 50% after this. National Forest System lands accounted for most (76%) of Colorado's timber products, followed by private and Native American lands (22%). As of 2020, 5.8 TgC was stored in harvested wood products that originated from Colorado's forests from 1954 to 2019, with 46% of this in solid waste disposal sites and the other 54% in products in use. As calculated by the IPCC production approach, harvested wood products have served as a carbon sink every year of the study period. This annual sequestration peaked at 0.2 TgC yr^{-1} in 1969 and was lowest in 2004 (0.01 TgC yr^{-1}). The ten-year average flux coincident with the forest ecosystem flux measurement period was 0.03 TgC yr^{-1}. Of the wood that was harvested from 1954 to 2019, 5.8 TgC is still being stored as wood products, while 9.5 TgC has been emitted with and without energy capture.

The harvested wood products stocks and fluxes were minor relative to Colorado's forest ecosystem carbon. The forest ecosystem held 99.6% of the combined carbon stocks (1,558.1 TgC). The state lost carbon from the forest sector at a rate of 3.2 TgCO2e yr^{-1} for the period tracking change between 2002 to 2009 and 2012 to 2019. Emissions were dominated by the forest ecosystem, while methane and nitrous oxide fire emissions contributed 3% of the forest sector flux. The net annual sequestration in harvested wood products was 4% of the magnitude of the forest sector carbon flux.

This report provides a comprehensive inventory of Colorado's forest ecosystem and harvested wood products. Our findings provide an improved understanding of the impact of disturbance, climate change, management and the wood products industry on forest carbon and how the state's forests are contributing to and mitigating climate change. The imprint of disturbances fueled by climate change and historical management legacies on the state's forest carbon stocks is evident as tree mortality, primarily from insect and disease, has outpaced carbon sequestered as growth during this study period. This inventory will be updated as data for recent years becomes available. We expect the magnitude of the carbon source to increase in future inventory iterations as the impact of the multiple large 2020 wildfires in Colorado begin to be reflected in plot remeasurements.

2 INTRODUCTION

2.1 Impetus

Colorado has a diverse forest ecosystem that also supplies a wide-ranging harvested wood products industry. Colorado's natural and working lands, including forests, rangelands, croplands and wetlands, among other lands, provide many climate mitigation and adaptation opportunities (Colorado Department of Natural Resources, 2023). Mitigating the effects of climate change is a priority for the state, and Colorado's legislative body established statewide objectives in 2019 aimed at curbing greenhouse gas emissions to a minimum reduction of 26% of 2005 levels by 2025, at least 50% by 2030, and 90% by 2050 under House Bill HB (HB) 19-1261. These goals were further refined in 2023 with Senate Bill (SB) 23-016, which introduced more reductions of 65% by 2035, 75% by 2040 and 90% by 2045, culminating in a revised 2050 target of 100% reductions. The 2020 Colorado Forest Action Plan identified the need for more targeted and detailed analyses of forest carbon to better understand the specific roles and impacts of the state's forested lands in climate mitigation, including their capacity for carbon sequestration and storage (Colorado State Forest Service, 2020). Forested lands can act as carbon sinks, absorbing more carbon than is released, or sources, releasing more carbon than is captured after events like wildfires. Recognizing these dynamics, Colorado lawmakers passed HB 22-1012, Wildfire Mitigation and Recovery directing the Colorado State Forest Service (CSFS) to develop a publicly accessible statewide carbon accounting framework which includes carbon flux and stock estimates for all forest types and wood products. This report addresses this directive and provides insights into the effects of changing environmental conditions and management activities on these forests, enabling more effective development and implementation of strategies for forest and carbon management.

2.2 Objectives and Scope

This report provides a comprehensive analysis of forest ecosystem and harvested wood product (HWP) carbon for Colorado while establishing a state framework to continue this monitoring in future years. The scope of this work includes Colorado's forests and the associated harvested wood products derived from these forests. Forest carbon in urban environments is not included in this report, as the data needed to incorporate urban forests are incomplete at this time. The framework, data sources, analysis and reporting leverage similar published reports from California (Christensen et al., 2019a), Oregon (Christensen et al., 2019b; Morgan et al., 2022) and Washington (Christensen et al., 2020; Nichols et al., 2020), providing consistency with the National Greenhouse Gas Inventory (NGHGI) and Intergovernmental Panel on Climate change (IPCC) guidelines and in comparisons between states. Central to our analysis is the utilization of the Forest Inventory and Analysis (FIA) program data and several harvest data sources. Forest carbon findings are summarized by multiple administrative boundaries including statewide, CSFS areas, counties, land ownership and forest type in addition to ecosystem processes (disturbance, pools, growth, mortality and removals). Forest carbon stocks are provided for the year 2019 using measurements collected from 2010 and 2019 and estimates of average annual net carbon fluxes are generated using remeasurement FIA data from 2002 to 2009 and 2012 to2019. Similarly, the Harvested Wood Product emissions are reported for the year 2019 and draw on harvest data spanning from 1954 to 2019. The carbon pools of focus in the forest ecosystem model are aboveground live tree and standing dead tree, belowground live and dead (i.e., tree roots), down woody material, aboveground and belowground understory vegetation, litter and soil. The carbon pools for the harvested wood products include harvested wood products in use (PIU) and in solid waste disposal sites (SWDS). Together these pools provide a total forest sector carbon inventory.

Objectives. The objectives for this report are as follows:

1. Develop a replicable Colorado forest carbon accounting inventory framework to enable future updates for monitoring and reporting and transferability to other states in the region.
2. Use the best-available forest inventory data to provide statewide estimates of forest carbon stocks and fluxes for Colorado.
3. Estimate harvests, stocks and fluxes of Colorado's harvested wood products and integrate with forest ecosystem carbon to provide a total forest sector carbon inventory for the state.
4. Summarize forest ecosystem carbon by pools, administrative boundaries, forest types and disturbances and summarize harvested wood product carbon by pools and ownership over time.

2.3 Forest Carbon Cycle

The forest carbon cycle is a complex process wherein carbon is exchanged between the forest ecosystem and the atmosphere. Through photosynthesis, trees absorb carbon dioxide (CO_2) from the atmosphere, convert it into organic matter, and store the carbon in a variety of biomass pools (Figure 1). Not all carbon fixed during photosynthesis is stored long-term in plants, as plants use a portion of photosynthate for maintenance respiration and other energy-requiring processes. Carbon pools within forests include aboveground live and dead biomass, belowground live and dead biomass, forest floor litter and soil. When trees die, they deposit litter and debris onto the forest floor and microorganisms break down this organic material, a process called decomposition. Decomposition releases carbon back into the atmosphere as CO_2, a process called respiration. However, not all carbon from the decomposed material is released back into the atmosphere and some remains in the soil, contributing to the soil carbon pool.

Natural disturbances such as wildfires, insect and disease outbreaks, windthrow and drought can cause significant tree mortality, potentially killing aboveground live vegetation over large areas. While tree mortality occurs naturally in all forests, it gradually releases carbon into the atmosphere. Generally, when a tree dies, the rate of carbon release depends on the decomposition of that material, related to the function of microorganisms, which is dictated by environmental factors such as moisture and growing season length. However, plants that die do not immediately shift to being carbon sources, as their mortality shifts carbon from the aboveground and belowground live pools to the aboveground and belowground dead pools. During a wildfire, some carbon, along with greenhouse gases such as methane and nitrous oxide, can be directly released to the atmosphere through the process of combustion. Additionally, human disturbances such as timber harvesting can remove carbon from forests. When timber is harvested from a landscape, much of the carbon is not immediately emitted to the atmosphere and is stored in various harvested wood products, making it a crucial element in carbon accounting. Two harvested wood products carbon pools are tracked when estimating harvested wood products flux: PIU and SWDS. These products, ranging from furniture to building materials can serve as long-term carbon reservoirs, effectively delaying the return of carbon to the atmosphere for decades, even centuries. Harvested wood products can also reduce emissions by substituting for more greenhouse gas intensive materials such as metals, although these benefits are not quantified in this report.

The balance between these carbon inputs (photosynthesis) and outputs (respiration, decomposition, combustion) determines the net carbon exchange between forests and the atmosphere and can indicate whether carbon emissions from forest ecosystems are stable, growing or declining. When a forest absorbs more carbon through photosynthesis than it releases through respiration, decomposition and combustion, it acts as a carbon sink. This can play a crucial role in mitigating climate change, as it reduces the overall

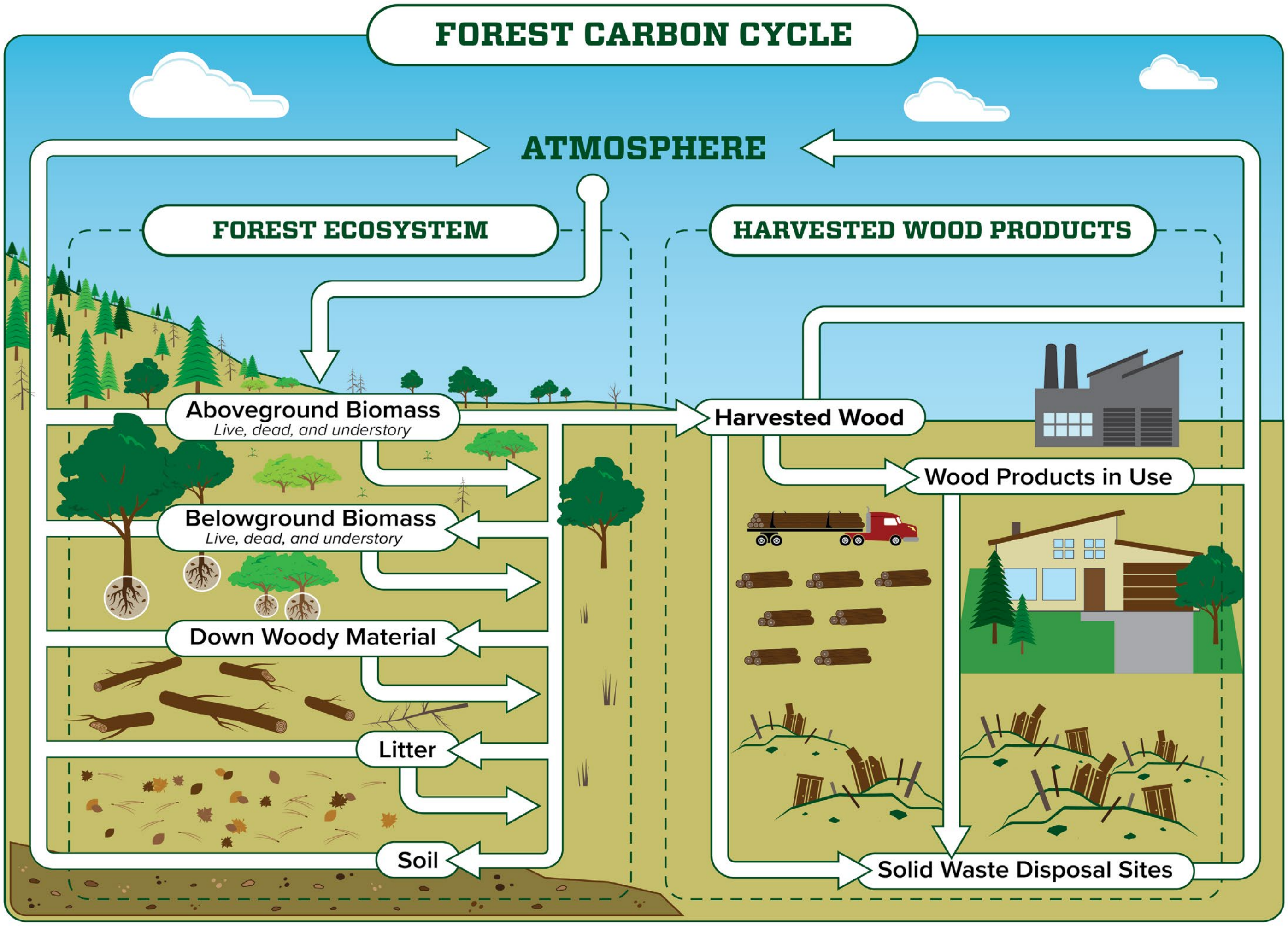


Illustration: Brian Sathe, Colorado State Forest Service

Figure 1. *This illustration depicts the forest carbon cycle as represented in this forest carbon inventory, highlighting the pathways through which carbon moves within and between forest ecosystems, harvested wood products and the atmosphere. The forest ecosystem includes aboveground biomass (live, dead and understory vegetation), belowground biomass (live, dead and understory), down woody material, litter and soil. All forest ecosystem pools have a pathway back to the atmosphere. Carbon stored in aboveground biomass (live or dead) can be transferred to harvested wood, which then follows different trajectories: wood products in use, solid waste disposal sites or back to the atmosphere. This cycle is continuous and dynamic, reflecting the constant changes of carbon between different pools through growth, disturbance, decomposition, harvest and utilization.*

amount of carbon dioxide in the atmosphere. However, forests can also become carbon sources if they release more carbon than they absorb. This often occurs due to disturbances such as wildfires or insect and disease outbreaks. As forests recover from these disturbances, they return to a sink. These disturbances, coupled with Colorado's inherent challenges such as low productivity, difficulties in regeneration, shifting climatic conditions and drought limit the ability of Colorado's forests to serve as net carbon sinks. Estimates since 1990 suggest that Colorado's forest ecosystems have been acting as a net source of carbon rather than a net sink (Domke et al., 2023). Other western states including Arizona, Idaho, Montana, New Mexico, Nevada, South Dakota, Utah and Wyoming are also net carbon sources (Domke et al., 2023).

2.4 Overview of Colorado Forests and Wood Products Industry

Colorado Forest Types and Ownerships

Colorado's approximately 22.8 million acres of forested lands (as measured by FIA data) can be classified into general forest types based on canopy cover, species composition and varied environmental conditions including elevation, climate and soils. The elevational gradient of forest types spans from plains cottonwood *(Populus deltoides)* and other riparian trees at the lowest elevations (3,350 to 7,500 feet), pinyon-juniper woodlands at low elevations (5,000 to 8,000 feet), to ponderosa pine *(Pinus ponderosa)*, Douglas-fir *(Pseudotsuga menziesii)* and aspen *(Populus tremuloides)* dominating the mid-elevations (6,000 to 9,000 feet), followed by lodgepole pine *(Pinus contorta)*, Engelmann spruce *(Picea engelmannii)*, subalpine fir *(Abies lasiocarpa)* and sometimes aspen in the high-elevation subalpine forests (9,000 to 11,500 feet) and ultimately transitioning to the treeless alpine tundra at the highest elevations (11,500 to 14,400 feet) (Colorado State Forest Service, 2020). Compared to forests in the eastern US or the Pacific Northwest, Colorado's forests tend to grow slower and are more moisture-limited due to the state's drier climate and shorter growing-seasons.

Land ownership in Colorado is divided between public and private ownership, ranging in size from a single acre to several million acres (Figure 2). Based on FIA data, approximately 71% (16.04 million acres) of Colorado's forests are in federal ownership; the primary land manager is the U.S. Forest Service with 48% (10.80 million acres). The Bureau of Land Management, National Park Service, Fish and Wildlife Service, Department of Defense, Department of Energy and other federal agencies oversee the remaining 23% of federal ownership (5.24 million acres). Despite the significant federal presence, private landowners and tribal governments also play an important role in managing Colorado's forest resources, making up approximately 26% (5.93 million acres). The remaining 3% (791,000 acres) of forested land is held by a combination of municipalities, state agencies and other non-federal entities.

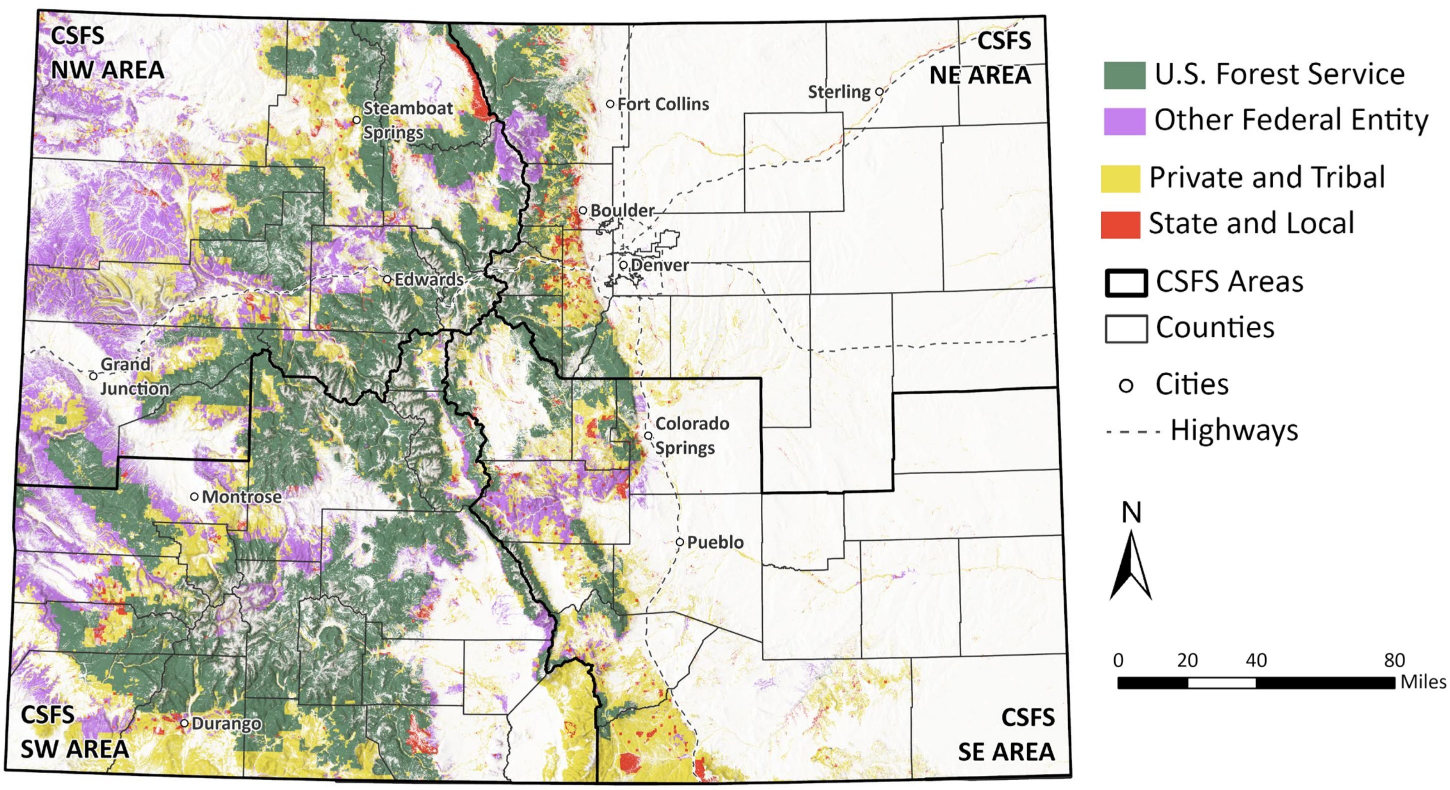


Figure 2. *Land ownership map of forested lands in Colorado. The state has four Colorado State Forest Service Areas (CSFS; Northwest (NW), Northeast (NE), Southwest (SW) and Southeast (SE)) (Colorado Natural Heritage Program, 2021; Colorado State Forest Service, 2023).*

Threats and Disturbances in Colorado's Forests

Colorado's forests face insect and disease cycles, wildfire, climate change, drought and human development. Colorado's forests have seen large-scale insect infestations, such as *Ips* beetles *(Ips sp.)* impacts on pinyon pine *(Pinus edulis)*, mountain pine beetle *(Dendroctonus ponderosae)* on lodgepole pine, spruce beetle *(Dendroctonus rufipennis)* on Engelmann spruce and western spruce budworm *(Choristoneura freemani)* across multiple species. Mountain pine beetle and spruce beetle alone have impacted over 20% of Colorado's forests since the turn of the century and have resulted in millions of acres with standing and down dead wood (Colorado State Forest Service, 2020). In addition, decades of fire suppression that began in the early 1890s in the western U.S. altered historical wildfire regimes of frequent-fire forests and led to forests that are unnaturally dense in historically fire-prone areas. This has escalated the occurrence of uncharacteristic wildfires with twenty of the state's largest wildfires recorded since 2001, including the top three in 2020; many of which were intensified by forests severely impacted by beetle infestations. Climate change and drought further exacerbates these conditions with warm, dry conditions and longer wildfire seasons (Bolinger et al., 2024). The increasing trend of uncharacteristic and characteristic wildfires is expected to continue based on climate predictions (Abatzoglou & Williams, 2016; Higuera et al., 2021; West et al., 2016; Westerling et al., 2006). There is high confidence in continued expected temperature increases, with lower confidence in expected precipitation changes, suggesting drought conditions and high evaporative demand will continue to interact with various forest disturbances for the foreseeable future (Bolinger et al., 2024). Insect and disease cycles, wildfire, climate change and drought directly influence the capacity of forests to capture and retain carbon. The Colorado State Forest Service's annual Report on the Health of Colorado's Forests provides an in-depth analysis of the trends affecting the state's forests.

Colorado Wood Products Industry

The wood products industry in Colorado is an important component of the state's economy, contributes to sustainable forest management and provides a long-term carbon sink depending on products produced. The industry spans from logging operations in forestlands to primary mills that process timber into raw materials like lumber and wood chips, as well as secondary manufacturers that create finished goods such as furniture, cabinetry and wood pellets. By providing jobs and contributing to local economies, the timber industry helps support communities located near forested areas. The industry is also critical to addressing forest health issues and wildfire risks, as sustainable timber harvest helps to thin overstocked forests and reduce fuels. Further, the wood products industry provides a long-term carbon sink, delaying the amount of carbon dioxide that enters the atmosphere at the time of harvest by continuing to store carbon for the duration of a wood product's lifespan.

Important Colorado timber species for the forest products industry include lodgepole pine, Engelmann and blue spruce, ponderosa pine, Douglas-fir, white fir, subalpine fir and aspen. Colorado has 10 million acres of non-reserved timberland defined as productive forestland that can grow commercial-grade timber and is not permanently reserved from utilization through statute or administrative designation (Irey, 2023). However, it is important to note that while the FIA program designates all state lands in Colorado as reserved, exceptions exist such as the Colorado State Forest near Walden, which despite its reserved classification, actively manages for wood production under a multi-use framework, along with other state-owned lands (Burrill et al., 2023; Colorado Parks and Wildlife, 2019). The estimated sawtimber volume on non-reserved lands in Colorado is 13.3 billion cubic feet (CSFS Biomass Assessment, in review). A 2014 survey identified 236 harvest contractors in the state, many of whom are small businesses. In 2020, there were 46 primary wood processing facilities in the state, down 142 from 2002 accounts (Irey, 2023). As estimated in 2020, 55% of Colorado lumber mills are small, producing less than 2 million board feet (166,666 cubic feet) annually, however the remaining 45% each produce greater than 11 million board feet (916,666 cubic feet) annually, for an average mill production of 5.3 million board feet (416,666 cubic feet) (Irey, 2023). The total timber processing capacity for the state is estimated to be 46,531 MCF (thousand cubic feet) and in 2016 only about 63% of capacity was utilized (Irey, 2023). Despite challenges such as fluctuating market demand and complex regulatory policies, the Colorado wood products industry remains an important component of the state's economy and a key player in maintaining the health and vitality of its forest ecosystems.

Statewide Biomass Assessment

In response to the 2020 wildfire season, the Colorado legislation passed HB 21-1180, Measures to Increase Biomass Utilization, establishing a grant program managed by the CSFS to promote biomass use for wildfire mitigation, renewable energy, soil health and carbon sequestration. With increasing federal and state investments in wildfire mitigation, there are increasing quantities of woody biomass removed from Colorado forests. Small niche operations that can process small-diameter, historically low-value or wood-considered waste are growing across the state as innovation in these markets increases. The CSFS has developed a statewide woody biomass assessment, detailing resource quantities, applications, costs, benefits and supply chain characteristics. This assessment supports HB 21-1180 and will guide policy and strategic planning related to natural resource management and climate action. Aligning with this carbon accounting framework, the statewide woody biomass assessment utilizes data from the U.S Forest Service (USFS) FIA program to estimate the volume of under-utilized woody material on non-reserved lands in the state. It is expected to be published in 2024.

2.5 Colorado Forest Carbon Policy

Statewide Legislative Measures

Colorado is a member of the U.S. Climate Alliance, a bipartisan coalition of governors, state agencies and nonprofit organizations committed to upholding the goals of the United Nations Framework Convention on Climate Change Paris Agreement. The alliance formed in June 2017 and members are committed to reducing their greenhouse gas (GHG) emissions, promoting clean energy and taking other actions to combat climate change. To help meet these goals, Colorado introduced two laws in 2019 (HB 1261 and Senate Bill 096) that established science-based targets of reducing statewide GHG emissions and monitoring of GHG emissions.

House Bill 19-1261, the Climate Action Plan to Reduce Pollution requires Colorado to reduce statewide GHG pollution to 26% of 2005 levels by 2025, 50% by 2030 and 90% by 2050. In 2023, Senate Bill 23-016 amended the targets set by HB 19-1261 to include reductions of 65% by 2035, 75% by 2040 and 90% by 2045, while also revising the 2050 target to 100% reductions. These targets apply to statewide GHG emissions and include emissions from electricity, transportation, industry, buildings and other sectors. The bill requires the Colorado Air Quality Control Commission to develop rules to achieve these targets and establish a framework for achieving them through stakeholder engagement and public input. Many counties throughout Colorado have adopted county specific climate action plans.

Senate Bill 19-096, Collect Long-term Climate Change Data requires the Colorado Department of Public Health and Environment (CDPHE) to collect and maintain long-term climate change data. This includes data on GHG emissions, climate-related impacts and progress towards meeting emission reduction targets. Senate Bill 19-096 requires CDPHE to develop a report every two years to assess the state's progress towards meeting emission reduction targets as established in HB 19-1261. Reports have been released in 2019, 2021 and 2023 (Heald, 2019; Taylor, 2021; Twyman et al., 2023).

Strategic Plans for GHG Reduction and Forest Management

To achieve HB 19-1261's targets, Governor Polis directed state agencies to develop a Greenhouse Gas Pollution Reduction Roadmap, which became available January 2021. The roadmap set a target to reduce emissions (or increase sequestration) on natural and working lands (NWL) by 1.0 million metric tons (Tg) of CO2e by 2030 from a 2005 baseline and outlined a set of strategies and actions to reduce emissions (Colorado Energy Office, 2021). By December 2022, more than 95% of the near-term actions identified in the roadmap were complete and the state released an updated GHG Reduction Roadmap ("Roadmap 2.0") in early 2024. A central element of the GHG reduction roadmap was the formulation of a strategic plan to maintain and enhance resilient carbon sequestration on NWL. The Strategic Plan for Climate-Smart Natural and Working Lands was published in 2023 (Colorado Department of Natural Resources, 2023) and the implementation of the strategic plan serves as a critical action item in the state's Roadmap 2.0 (Colorado Energy Office, 2024).

In 2020, the CSFS produced a Colorado Forest Action Plan as required by the Cooperative Forestry Assistance Act of 1978, passed by Congress and amended by the 2008 and 2014 U.S. farm bills. This plan outlined goals, strategies and approaches for addressing challenges in forest conditions, living with wildfire, watershed protection, forest wildlife, urban and community forestry and forest products themes. These goals, strategies and approaches were developed using a climate change response framework that includes menus for climate adaptation (Swanston et al., 2016). Additionally, this plan identified the need for more targeted and detailed analyses of forest carbon to better understand the specific roles and impacts of the state's forests in climate mitigation, including their capacity for carbon sequestration and storage (Colorado State Forest Service, 2020).

Economic and Legislative Support for Forest Carbon Initiatives

To help achieve HB 19-1261 and the natural and working lands target goals, various national and statewide efforts have been launched to promote carbon-smart land management, or practices that promote carbon sequestration and GHG emission reductions from land use activities. At the national level, the 2022 Federal Inflation Reduction Act (IRA) provides incentives and policy tools to reduce national GHG emissions. The IRA includes critical funding for climate-smart forestry conservation incentives for private forest landowners, wood innovation grants, the Forest Legacy Program, an inventory of old-growth and mature forests in the National Forest System (NFS) and wildfire risk reduction.

The Colorado Legislature has established various funding sources aimed at reducing wildfire risk and promoting forest health on the ground. Key programs include the Forest Restoration & Wildfire Risk Mitigation (FRWRM) Grant Program, expanded by SB 21-205 for community-level wildfire risk reduction, forest health and woody material utilization. The Incentives for Local Government Grant Program (HB 22-1011) supports local forest management and wildfire mitigation with state funds. Additionally, the Colorado legislature passed Senate Bill 21-258, which created the Colorado Strategic Wildfire Action Program administered by the Department of Natural Resources (DNR). This program invests in wildfire risk mitigation projects and workforce development.

A snowpack monitoring project led by the Colorado Water Conservation Board and aided by the Colorado State Forest Service Monitoring Team is gathering data to support an experimental forest thinning project. ***Photo: Field Peterson, CSFS***

Moreover, the state has taken further steps towards addressing the impacts of wildfires and promoting forest health through HB 22-1012, *Wildfire Mitigation and Recovery.* This legislation requires CSFS to develop a publicly accessible statewide carbon accounting framework. The bill defines a *carbon accounting framework as:*

"A model that uses data from the Forest Inventory and Analysis program of the United States Department of Agriculture's Forest Service to develop tabular data of carbon flux and stock estimates for all forest types and wood products in the state of Colorado."

This report is the first in a series of reports and tabular data are available.

2.6 Other Colorado Forest Carbon Inventory Publications

Recent efforts have estimated forest carbon stocks and fluxes in Colorado through both national and state level analyses, detailed in Appendix A. Key publications include the U.S. Environmental Protection Agency (EPA) annual U.S. National Greenhouse Gas Inventory (NGHGI) (U.S. EPA, 2023b) statewide GHG inventories by the Colorado Department of Public Health and the Environment (Twyman et al., 2023) and research by Hoover & Smith (2021). While these publications vary in detail due to different mandates and audiences, many follow the Intergovernmental Panel on Climate Change's (IPCC) framework for reporting GHG inventories in the Land Use, Land-Use Change and Forestry (LULUCF) sector. The primary data source for assessing forest carbon in the US is the USFS FIA program, which utilizes a widely accepted definition of forest land detailed in Section 3.1. This definition guides the identification of specific lands covered in these publications.

The latest NGHGI report provides annual stock and flux data spanning from 1990 to 2021 and estimates that from 2021 to 2022, Colorado's forests were a net source of carbon among forest categories (forest remaining forest, land converted to forest and forest converted to other land covers), with a release of -12.6 $TgCO_2e$ yr^{-1} (Walters et al., 2023). The harvested wood product estimates in the NGHGI are not disaggregated by state and only national estimates are available from this report (U.S. EPA, 2023b). The CDPHE reported Colorado's forests to also be a net source of GHG emissions (-10.67 $TgCO_2e$ yr^{-1} without HWP included and -10.12 $TgCO_2e$ yr^{-1} with HWP included) in 2018 (Taylor, 2021). In 2023, CDPHE released an update which divides emissions between two categories: forest land remaining forestland (-11.51 $TgCO_2e$ yr^{-1}) and land converted to forest land (0.99 $TgCO_2e$ yr^{-1}) using data through 2020 (Twyman et al., 2023). This recent report does not provide estimates for harvested wood products. Hoover & Smith (2021) estimated Colorado to be a carbon source but only included the aboveground live tree pool (-15.17 $TgCO_2e$ yr^{-1}). More details on carbon stocks and fluxes from these reports and comparisons to findings from this inventory are provided in the Discussion and in Appendix A.

3 METHODS

This report adopted similar methodology and structure to forest carbon inventory reports compiled for California (Christensen et al., 2019a), Oregon (Christensen et al., 2019b; Morgan et al., 2022) and Washington (Christensen et al., 2020; Nichols et al., 2020). These reports provide a detailed and transparent inventory of the carbon stocks and fluxes for the forest ecosystem and harvested wood products of their respective states and use data sources and analyses that can be adopted by other states, including Colorado. Many of the methods and data sources presented below are discussed in detail in these reports and are only briefly discussed here and direct readers to these reports for more information.

3.1 Forest Ecosystem Carbon Inventory Methods

Alignment to IPCC Inventory Approach

This report adapts the forest ecosystem carbon inventory framework established by California, incorporating IPCC guidelines for key emission categories associated with forest lands. It concentrates on Forest Land, one of the six land-use categories outlined in the IPCC's LULUCF categories. The definition of forest land employed in this report is based on the FIA definition (defined below). All land in the lower 48 and in Colorado is considered 'managed' per the IPCC definition and therefore all forested land in Colorado, as defined by FIA, was included in this analysis.

The IPCC framework is structured into three tiers, reflecting increasing levels of data detail and methodological complexity. These tiers allow countries to report with varying degrees of accuracy based on their capabilities and data availability. This report uses Tier 3 (the most rigorous tier) when possible, incorporating direct measurements, high resolution data and methods that are transparent and verifiable. However, this was not a requirement of this report and in some cases our estimates may not meet all IPCC Tier 3 requirements (IPCC, 2006, 2014). This analysis did not include N_20 emissions from forests. In addition, changes in land use from non-forest to forested land and forested land to non-forest is not accounted for (reasoning for this explained below); this report only considers plots that were forested at both measurement periods for fluxes and plots forested at the time of measurement for stocks.

There are generally two IPCC Tier 3 methods to estimate carbon flux. The first method, known as the stock-difference approach involves calculating the difference in individual carbon pools at two points in time. This approach considers the net change in carbon storage without explicitly tracking the individual tree processes. The second method, used in this report, involves analyzing differences in remeasured data, where the most recent survey results are paired with measurements from a previous survey on the same plot. This allows for more precise accounting since it tracks individual processes such as growth, removals and mortality and associated carbon fluxes. FIA defines this as the growth, removals and mortality (GRM) approach.

Forest Inventory and Analysis Design

The core dataset used for U.S. carbon inventories in forested ecosystems is from the Forest Inventory and Analysis (FIA) program, a nationwide inventory of US forestlands maintained by the USDA Forest Service. The program is designed to assess the status and trends of forests across all landownerships and forest types. The network comprises permanent, geographically unbiased field plots at a density of approximately one per 6,000 acres (Bechtold & Patterson, 2015). In the late 1990s, the FIA program transitioned to an annual inventory system in every state and nationally consistent data collection. In the Interior West, 10% of plots are measured each year, which equates to a complete sample of all forest inventory plots every 10 years. Colorado's annual inventory began in 2002 and completed the first full annualized inventory cycle in 2011. In 2012, FIA began re-measuring the same plot locations as established in 2002 and began the third re-measurement cycle in 2022. Although the third re-measurement cycle in Colorado is currently being conducted, as of late 2023 only annualized data up to 2019 are available to the public. This report uses the first cycle of annual inventory in Colorado (2002 to 2011) and eight years of re-measurement data (2012 to 2019). All FIA data are freely available to the public and are deposited in the FIA DataMart located at *https://apps.fs.usda.gov/fia/datamart/datamart.html*. This report used version 9.1 of the FIA database accessed on Dec 8th, 2023. The sampling design and associated measurements of FIA data allow the ability to calculate standard errors and uncertainty, which are provided in this report, except for fluxes in the aboveground down wood pool (discussed below).

The FIA land status distinguishes forest land from non-forest land (i.e., crops, improved pasture, residential areas, city parks, etc.) and other areas (i.e., water). Forest land is defined as land that is at least 120 feet wide and 1 acre in size, has at least 10% canopy cover of live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated (Forest Inventory and Analysis, 2023). Areas that do not currently meet the tree canopy cover criterion but are expected to in the future (e.g., because they were recently logged or burned) can also be considered forest land. Forest land can include transition zones, such as areas between forest and non-forest lands adjacent to urban and built-up lands with live trees if they meet the percent cover and size requirements. Similarly, unimproved roads and trails, streams and clearings in forest areas are classified as forest if they are less than 120 feet wide or an acre in size. Forest land does not include land that is primarily used for non-forest purposes, such as agricultural or urban land use.

This report uses the FIA definition of forest lands and does not make any changes to exclude plots that would not meet forest land definitions based on in situ criteria (Forest Inventory and Analysis, 2023). Forest definitions depend on the cover requirements mentioned above, but also species requirements based on the FIA complete forest tree species list. So long as areas with woodland species meet the forest land size, species and cover requirements, they are considered forested. If they do not meet the forest land size, species and cover requirements, FIA classifies the condition as non-forest. This is an important distinction from the NGHGI publications and the Walters et al. 2023 dataset covered elsewhere in this report because these other inventories classify areas with woody species that do not meet the forest land requirements as woodlands. Other similar reports to this report have re-classified some FIA-defined forests as woodlands to add greater distinction between certain forest types (Christensen et al., 2019a).

The management practices and utilization of forest land are frequently determined by who owns the land and its designated status. The FIA owner group indicates the ownership category and includes four categories: Forest Service, other federal, state and local government and private (Table 1). On publicly owned land, FIA assigns a reserve status to areas permanently restricted from wood product production by law or agency mandate (i.e., wilderness designation, National Monument, National Parks, etc.).

Table 1. *Forest Inventory and Analysis land ownership groupings and associated descriptions.*

OWNERSHIP GROUP	DESCRIPTION
Forest Service	National Forest; other Forest Service land
Other Federal	National Park Service; Bureau of Land Management; Fish and Wildlife Service; Departments of Defense/ Energy; Other Federal
State and Local Government	State including State public universities; Local (County, Municipality, etc.); Other non-Federal public
Private	Undifferentiated private and Native American

Disturbances and treatments that have occurred on a plot since the previous measurement are recorded by FIA crews. Up to three disturbances and three management treatments can be coded. The area affected by any natural or human-caused disturbance must be at least one acre in size and at least 25% of all trees in a stand or 50% of an individual species' count must exhibit damage or mortality.

Disturbances and treatments that have occurred on a plot since the previous measurement are recorded by FIA crews. Up to three disturbances and three management treatments can be coded. The area affected by any natural or human-caused disturbance must be at least one acre in size and at least 25% of all trees in a stand or 50% of an individual species' count must exhibit damage or mortality. Disturbances include insect damage, disease damage, fire, animal damage, weather damage, geologic disturbances and others. Forestry treatments are a form of disturbance but are recorded separately and imply that a silvicultural application has been prescribed. The area affected by any treatment must be at least one acre in size and includes cutting, site preparation, artificial regeneration, natural regeneration and other silvicultural treatments.

Carbon Pool Calculations

The carbon pools and calculations in this report are similar to those presented in the California report (Christensen et al., 2019a) where the pool descriptions, the equations used to calculate components of each pool and their associated references are listed. However, since the California report was published, the FIA database has been updated with the National Scale Volume and Biomass (NSVB) modeling methods for estimating cubic-foot volume, biomass and carbon attributes of each tree (Westfall et al., 2023). We updated carbon calculations to account for key changes with the adoption of NSVB such as updated tree component categories and the application of species-specific carbon fractions. Below is a description of each pool:

- *Aboveground live tree.* All live trees greater than or equal to 1.0 inch diameter at breast height (DBH) or 1.0 inch diameter at root collar (DRC) for woodland species are included in this pool.
- *Aboveground standing dead tree.* This pool includes standing dead trees that are greater than or equal to 5.0 inches DBH or DRC.
- *Belowground live and dead.* This pool includes live and dead tree roots, disaggregated into belowground live and belowground dead in this report.
- *Down woody material.* Carbon pool of down woody material as defined in the FIA protocol.
- *Aboveground and belowground understory vegetation.* This pool is modeled from live tree carbon, geographic area, forest type and plot characteristics. It includes the aboveground and belowground components of woody shrubs and seedlings less than 1.0 inch DBH or DRC.
- *Litter.* This carbon pool includes forest floor duff and litter and was modeled as described in Domke et al. (2016).
- *Soil.* This pool includes soil organic carbon up to 1 meter in depth and is based on the model provided in Domke et al. (2017).

Stock and Flux Calculations

Carbon stocks were calculated using ten years of plot data (2010 to 2019), a full ten-year panel of plots. We calculated stocks from plots that were forested when the plots were measured. We calculated the average annual net carbon flux from plots initially measured between 2002 to 2009 and remeasured from 2012 to 2019. As mentioned above, this report calculates the change in forest carbon pools by tracking the growth, removals and mortality (GRM) of trees re-measured ten years apart on FIA plots. Only plots that were forested at both measurement periods were considered for flux estimates. The unforested plot designation can result from FIA protocol definitional change or field crew interpretation and may not reflect true forest change. Furthermore, some carbon pools, namely soil carbon, are not modeled on unforested plots. We calculated the area that changed from forested to unforested or unforested to forested during this measurement period and it was found to be about 5% of the forested remaining forested area. This is a high estimate, as a process of verifying changes in FIA classifications would likely reduce, not increase the number of changed plots/area.

Estimates were assigned based on the condition (e.g., ownership, forest type, etc.) of the initial measurement between remeasurements. In instances where live trees died or were cut between measurements, growth equations were used to estimate tree diameter and height at the midpoint (typically 5 years) of the measurement interval and to calculate carbon at the time of death or removal (Bechtold and Patterson 2005). Conversely, if new trees grew into the sapling size class between measurements, they were considered ingrowth. Changes in live tree carbon can be partitioned into three categories of growth, removal or mortality. Standing dead tree carbon fluxes were estimated from the differences in this carbon pool between measurements and could include live tree carbon entering this pool from mortality and dead tree carbon leaving the pool through decay (as documented through decay class data recorded for each tree), transition to another pool, or combustion from wildfire. In instances where trees fell, their carbon moved to the down woody material pool in the second measurement. In instances of harvest, the tree's carbon is represented as a loss from the ecosystem for the second measurement. While the HWP model captures the fate of harvested carbon, it uses separate data sources and is not linked to specific removal estimates as captured by FIA data.

Carbon *stocks* in the down woody material (DWM) pool were calculated in a comparable manner and across the same plots as other carbon pool stocks for this report. However, DWM flux (but not stock) calculations were affected by procedural changes for measuring DWM in the Rocky Mountain FIA region. Three different methods have been employed for measuring DWM from 2002 to 2019. Furthermore, DWM stocks were initially only measured on FIA Phase 3 plots, which constitute 1/16th of the FIA grid plots. So, while the second measurement of each plot (2012 to 2019) included DWM, many plots were missing DWM estimates during their first measurement. Thus, we only used Phase 3 plots for calculating DWM flux as these were the only plots where change in DWM could be calculated. Even these plots often had different DWM methods between initial and re-measurement that we standardized for, such as different transect lengths. Other procedural differences introduce further uncertainty in the DWM estimates, such as transects being located between subplots at initial measurement and then moved to be within the subplot at the second measurement. A stratification based on remeasured FIA Phase 3 plots was created to calculate the DWM flux. Given that DWM fluxes were calculated from far fewer plots (roughly 1/16th) than other fluxes, the sampling error is much larger and cannot easily be combined with other standard errors. Thus, we only report standard error for the net flux without DWM and do not report standard error with the net flux that includes DWM. Furthermore, DWM flux is not available for smaller areas (e.g., less common disturbances like "cut and fire") since the plot density of Phase 3 plots is sparser.

Fire Emissions

We calculated methane (CH_4) and nitrous oxide (N_2O) emissions from fire following the methods of (Christensen et al., 2019a) which is a modification of the IPCC (2006) methods. We treated the net flux in plots classified as having "fire" and "cut and fire" as the carbon lost to fire, although some of this flux could be exaggerated (cutting before the fire, post fire decay of tress) or minimized (tree recovery after fire). Even with these assumptions, we feel this estimate of consumed material to be more accurate than applying generalized combustions factors to pre-fire biomass values as is done in the default IPCC (2006) approach. The carbon lost from the "fire" and "cut and fire" plots were multiplied by emissions factors (CH_4 = 4.7, N_2O = 0.26 g kg^{-1} of dry matter burnt; IPCC 2006) to estimate the mass of methane and nitrous oxide emitted. Lastly, the masses were converted to CO_2 equivalents, which accounts for the 100-year global warming potential of these gases (CH_4 = 25, N_2O = 298; IPCC (2007)). Similar to Christensen et al. (2019a) and the NGHGI (U.S. EPA, 2023b), we only calculated emissions for these primary non-CO_2 fire emissions (methane and nitrous oxide) and did not include others such as non-methane volatile organic compounds, carbon monoxide and nitrogen oxides as we did not find greenhouse gas equivalents for these.

3.2 Harvested Wood Products Methods

Background

When trees are harvested, some material remains onsite usually in the form of slash. Unused biomass either decays and cycles through the forest ecosystem's carbon pools or is combusted on-site, emitting carbon and GHGs. Conversely, material removed from the forest can be stored as carbon in wood products, serving as a carbon sink for the product's lifecycle. As defined by the IPCC, harvested wood products includes primary products made from wood including lumber, panels, paper, paperboard and wood used for fuel or end use products such as houses or furniture (IPCC, 2006, 2014; Skog 2008). The IPCC recognizes two primary carbon pools in harvested wood products: products in active use (PIU) and products that have been discarded to solid waste disposal sites (SWDS). PIU represents wood products in active use, serving as carbon sinks. The carbon contained in discarded products entering SWDS may be released many years or decades later or may be stored almost permanently depending on the manner of disposal (e.g. anaerobic landfills, sealed landfills, methane capture and combustion) (U.S. EPA, 2023b).

Approaches to estimating carbon in harvested wood products have been developed for the national level (Skog, 2008) and regional USFS level (e.g., Stockmann et al., 2014), which follow the IPCC's Tier 3 production approach (IPCC, 2006, 2014). This led to the development of a USFS harvested wood products carbon model which used the IPCC production method. This model was modified to allow for harvest from different ownerships to be run simultaneously and to provide greater access to required datasets for use in state-level harvested wood products carbon inventories. Later, through a partnership between the California Department of Forestry and Fire Protection (CAL FIRE), Oregon Department of Forestry (ODF) and Groom Analytics LLC, this model was further modified to run with R code and provide outputs that can also accommodate the IPCC simple-decay method. The states of California, Oregon and Washington have used this latest harvested wood products carbon model for their state accounting and this report follows the same methodology.

Since 2003, nearly 90 percent of the spruce-fir zone on the Rio Grande National Forest has been impacted by wide-spread spruce beetle and Douglas-fir beetle populations, including this site near Wolf Creek Pass Ski Area in southwest Colorado. ***Photo: Adam Moore, CSFS***

This report aligns with the IPCC in identifying only PIU and SWDS as reportable harvested wood products storage pools within the forest sector under the IPCC production approach. Although harvested wood that is emitted with energy capture (EEC) or without (EWOEC) is crucial for other harvested wood products IPCC approaches and broader carbon accounting (e.g., the energy sector), it is not included in the forest sector under the IPCC production approach. Products in the SWDS represent stored carbon but can aid in estimating methane emissions from landfills in the waste sector. Information from this report can support CDPHE's biennial GHG inventories.

Here, carbon stocks in Colorado's harvested wood products are assessed using a production approach, accounting for timber harvested statewide, whether used within the state or exported to other states or countries. Imported wood products are excluded because the emphasis in the production approach is on the location of harvest. All carbon emission estimates from this harvested wood products model are for the biogenic carbon content of the harvested wood only and do not include emissions in the form of other carbon-containing greenhouse gases such as methane. The modeling framework for the forest sector does not include estimates for the GHG emissions associated with timber harvesting, log transportation, harvested wood products manufacturing, substitution effects of wood products, bioenergy or leakage.

Overview of the Harvested Wood Products Carbon Model

The state-variant of the harvested wood products carbon model was programmed in R by Groom Analytics LLC and is available via GitHub and can be run as an R Shiny App (Groom & Tase, 2022). The model employs a series of calculations, based on the Tier 3 production approach carbon estimation guidelines from the IPCC, to determine cumulative carbon stocks and emissions from both current and historic timber harvests used for wood products. Carbon in harvested wood products is tracked through a product's life, from timber harvest through timber products, primary wood products, end use products and finally to disposal (Figure 3; Stockmann et al., 2014). The model provides cumulative carbon storage and emissions for all harvest years analyzed.

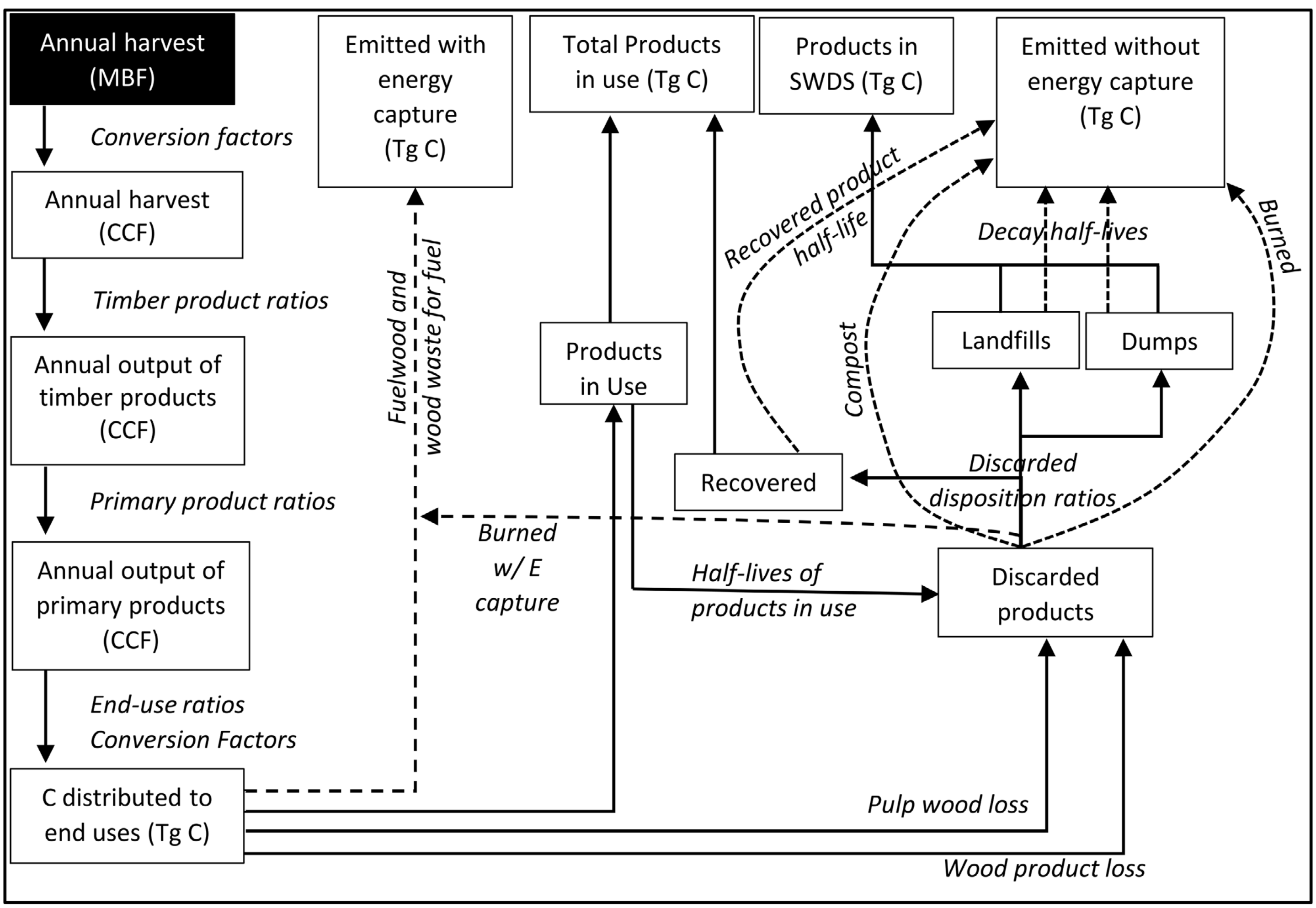


Figure 3. This figure illustrates the harvested wood products model used to quantify carbon storage pools and emissions. It shows the stages of carbon distribution from the annual harvest through various product outputs to end uses, and tracks the pathways to emissions, products in use and solid waste disposal sites. Adapted by Groom & Tase (2022) from Stockmann et al., (2014).

We used Groom Analytics' harvested wood products model template for the Rocky Mountain region to construct the input file for the harvested wood products model. We relied on default data provided in the template except for annual harvest data and timber product ratios (see Colorado Data Sources below). A copy of our input file is provided in Supplemental File 1. The model divides annual timber harvests in thousand board feet (MBF) into various timber products (such as sawlogs and pulpwood) and primary products (such as lumber and panels) using timber product ratios (TPR) and default primary product ratios (PPR) provided in the template from Smith et al. (2006). Conversion factors were used to convert harvest volumes in MBF to cubic foot volumes (U.S. Department of Agriculture, 2022 and Stockmann 2023 correspondence). This volume, in cubic feet, is then translated to carbon units (TgC) using methodologies from Skog (2008) and Smith et al. (2006). Primary products are then distributed to end uses using end use ratios (EUR), ranging from single-family new housing and furniture manufacturing, derived from McKeever (2009) and McKeever & Howard (2011). The carbon associated with primary products in each end-use comprises the PIU of the harvested wood products model (Groom & Tase, 2022).

Once wood products are retired, they can be recycled or recovered (re-entering the in-use pool), as represented by the product half-lives (Figure 3). National default values from Smith et al. (2006) were used. Products with no further half-lives undergo processes such as disposal at SWDS, composting, or incineration using discard disposition ratios (Skog, 2008). Products that undergo immediate oxidation include those burned (with or without energy capture) or composted. Products that are sent to landfills and dumps (which comprise the SWDS pool) represent storage pathways. The carbon amount that remains inert in landfill anaerobic environments is indicated by the landfill fixed carbon ratio (Skog, 2008). To estimate the carbon emission rate from the SWDS pool, decay half-lives are applied to dumps and the decaying portions in landfills. The model also conducts a Monte Carlo analysis of uncertainty of 16 different input parameters. Christensen et al. (2019a) and Stockmann et al., (2014) provide more details of the model assumptions, calculations and data sources for required data inputs.

Stocks and changes from the harvested wood products were combined with forest ecosystem stocks and fluxes to provide net stocks and fluxes for the forest sector. We summarized harvested wood products data to align with FIA plot sampling periods and offset the harvested wood products data summaries by one year from the FIA measurement years since the harvested wood products get reported one year following harvest by the harvested wood products model. Since forest ecosystem stocks are calculated by plots measured between 2010 and 2019, harvested wood products stocks were calculated as the average harvested wood products stock from 2011 to 2020. This stock includes PIU and SWDS. Average forest ecosystem fluxes are calculated from FIA plots measured between 2002 to 2009 and remeasured between 2012 to 2019, so changes in harvested wood products carbon were calculated as the average annual flux (annual change in PIU and SWDS) of eight periods: 2003 to 2013, 2004 to 2014, 2005 to 2015, 2006 to 2016, 2007 to 2017, 2008 to 2018, 2009 to 2019 and 2010 to 2020.

Colorado Data Sources

This report used Colorado specific data for annual harvests and timber product ratios. Harvest data was compiled from many sources and the land ownership was assigned to one of five categories to ensure consistency with the forest ecosystem model: National Forest System (NFS), other federal government, state and local government, Native American and private. Native American and private land were combined into one category. Annual harvest data sources include Western Wood Products Association (WWPA) yearbooks, USDA Four Corner reports, USFS Cut and Sold Reports and data from the Bureau of Land Management (BLM). Each source offered data for varying years and ownership categories (Figure 4).

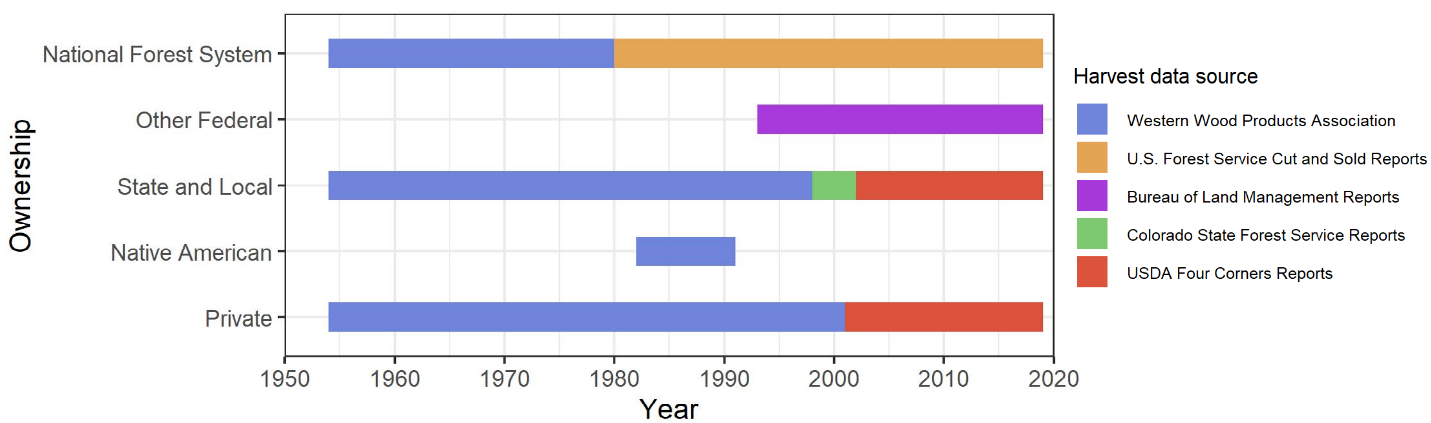


Figure 4. *Data sources and associated years of data used to extract annual harvest data for each land ownership category from 1954 to 2019. The Other Federal category includes Bureau of Land Management land. Native American was later combined with Private ownership.*

The WWPA produces many publications including Statistical Yearbooks, which are an annual summary of Western softwood lumber production activity by Western state, region and species. Publications began in 1968 with intermittent data starting in 1954. The data is developed from annual surveys of all mills in the West. In 2000, the formatting of the yearbooks changed, which discontinued state-wide reporting. We utilized data from 1954 to 2000 with the following ownership breakdowns: NFS: 1954 to 1979, State/local government: 1954 to1998, Native American: 12982 to1991 and Private: 1954 to 2000 (Western Wood Products Association, 2000; Figure 4). The USDA produces timber harvest and forest products industry reports for the four corners region, which includes Colorado. This report used the timber harvest reports from the 2002, 2007, 2012 and 2016 USDA Four Corners reports for only private and state/local government ownerships (Hayes et al., 2012, 2021; Morgan et al., 2006; Sorenson et al., 2016).

The USFS began reporting sales of forest products and harvest or removal of forest products for NFS lands in 1977, known as Cut and Sold Reports. Reports are provided by region and further divided by forest. From 1977 to 2008 values were reported through the Automated Timber Sale Accounting system and from 2009 to 2022 the data is published from the USFS's Corporate Data Warehouse. Pre-1980 data was not included due to a lack of supporting documentation. USFS Cut and Sold Reports from 1980 to 2019 were utilized (U.S. Department of Agriculture, 2022). The Other Federal ownership category consists of only BLM harvest data but was titled Other Federal to be consistent with FIA ownership groupings. The BLM data was provided through CSFS and agency communication. It was provided in three parts: the Stewardship Contracting Information Database (SCID), the Special Forest Products (SFP) and the Timber Sale Information System (TSIS) (Bureau of Land Management, 2023). The BLM data was available from 1993 to 2019. A systematic approach was utilized to consolidate and merge these datasets, as described in Appendix B.

The timber product ratios (TPR) allocate harvest to different timber product classes. There are 40 timber product classes available in the model, 20 classes each for softwood and hardwoods. Annual TPR is the portion of the annual harvest classified as specific timber products, such as sawtimber, pulpwood, posts and fuelwood. The USFS Cut and Sold Reports from 1980 to 2008 and those from 2009 to 2019 were the main data sources for TPR due to their extensive temporal coverage, open-source availability and finer detail compared to other data sources.

Product data was available for 21 timber product classes in Colorado from 1954 to 2019. Most of the harvested timber were softwood sawtimber, softwood fuelwood, hardwood miscellaneous, softwood miscellaneous, hardwood sawtimber and softwood poles. See Appendix B for the approaches used for handling materials without hardwood or softwood designation, dead material categorization, addressing category mismatches and other items to match the model's worksheet template.

Uncertainty Analysis

The harvested wood products model utilizes a Monte Carlo (MC) analysis of uncertainty to produce estimates and confidence intervals for overall values for SWDS, PIU, EWOEC, EEC and their combinations. The goal of the MC simulation was to produce 90% confidence intervals for the cumulative amount of carbon classified in the four categories. This approach enables the MC analysis to explore a range of possible outcomes under varying levels of data certainty. To achieve this, the MC analysis alters the values of 16 different variables within the model according to their associated parameters. Two thousand iterations were done to achieve stable estimates. The variability of the 16 variables was determined based on Skog (2008). Random values were drawn from triangular distributions that have a peak value of 1.0 and symmetrically taper to given 90% confidence interval bounds. The random values from the triangular distribution were used as proportions for adjusting parameter values for each iteration of the simulation.

3.3 Measurement Units and Statistical Interpretation

Units for carbon stocks are provided in teragrams of carbon (TgC; equivalent to million metric tons or MMT C). Carbon flux values are provided in units of annual average teragrams of carbon per year (TgC yr^{-1}) and carbon dioxide equivalent per year ($TgCO_2e$ yr^{-1}). To convert TgC to $TgCO_2e$, TgC can be multiplied by 3.6667, since the molecular weight of CO_2 is about 3.6667 times that of carbon. We define flux as a change in carbon as it moves to another pool (e.g., transfer from live aboveground to dead aboveground when a tree dies), the atmosphere (e.g., decomposition of dead trees), or harvested wood products (i.e., cut trees). Negative fluxes represent a loss from that pool and positive fluxes represent growth in that pool. The negative net fluxes for Colorado's forests represent overall loss of carbon from the forest ecosystem as carbon moves primarily to the atmosphere and, to a lesser extent, harvested wood products and other mechanisms of export from the ecosystem. Carbon densities refer to the ecosystem carbon per unit area and are reported in megagrams (Mg; equivalent to a metric ton) per hectare (ha).

We generally report to the thousandth Tg. We show <0.001 for positive values less than 0.0005 (due to rounding) and greater than zero and >-0.001 in tables for negative values greater than –0.0005 and less than zero. Ranges in the text presented for forest ecosystem results (i.e., ±) represent a 95% confidence interval (CI), while values in the tables report the sampling error (SE; CI = 1.96*SE). The harvested wood products results have a 90% CI from the Monte Carlo analysis (Section 3.2).

4 FOREST ECOSYSTEM CARBON RESULTS

4.1 Statewide Forest Carbon Stocks and Fluxes

Forest carbon stocks in this report are for lands forested at the time of measurement from 2010 to 2019 and fluxes are for lands that were forested across both measurement times (2002 to 2009 and 2012 to 2019). Fluxes exclude lands that changed between forest and non-forest during this period, although this area and the associated stock/ flux is estimated to be small for Colorado (see section 3.1 for a more in-depth discussion of this). Carbon stocks are calculated using the same plots for each pool, but for fluxes, down woody material (DWM) was calculated on a subset of plots and thus has higher sampling error. For this reason, we show net fluxes without DWM with standard error and net fluxes including DWM without standard error (see section 3.1.4 for a more in-depth discussion of this). This section further describes the statewide results from the forest ecosystem model and presents the ecosystem processes (i.e., disturbance, pools, growth, mortality and removals) underlying the state's forest carbon stocks and fluxes. We also present the forest carbon stocks and fluxes by forest type group.

Colorado's forests held 1,552.597 ± 23.532 TgC for plots measured between 2010 and 2019 and emitted 0.867 TgC yr^{-1} based on plots first measured between 2002 to 2009 and re-measured from 2012 to 2019 (Table 2). The flux without DWM was –1.863 ± 0.453 TgC yr^{-1}.

Table 2. *Statewide carbon pool stock for forested lands from FIA plots measured between 2010 and 2019. The average annual net flux is shown for Colorado's forest lands remaining forested for plots measured between 2002 to 2009 and 2012 to 2019.*

	Stock		Flux	
	Total	**SE**	**Total**	**SE**
	TgC		*TgC yr^{-1}*	
Aboveground live	311.617	4.045	-3.824	0.279
Growth	-	-	*5.035*	*0.076*
Removal	-	-	*-0.377*	*0.062*
Mortality	-	-	*-8.483*	*0.282*
Aboveground dead	67.015	1.959	2.664	0.200
Belowground live	53.728	0.689	-0.956	0.048
Belowground dead	14.293	0.409	0.567	0.040
Down woody material	62.320	1.124	0.995 *	0.425 *
Litter	96.316	0.840	-0.436	0.034
Aboveground understory	22.064	0.239	0.078	0.011
Belowground understory	2.452	0.027	0.009	0.001
Soil	922.792	7.855	0.036	0.048
Total without down woody material	-	-	-1.863	0.232
Total	1,552.597	12.006	-0.867 **	- **

** Flux of the down woody material pool is calculated from a subset of plots*

*** Standard error not presented for total with down woody material*

Forest Carbon Pools

Aboveground carbon (i.e., down woody material, litter, aboveground live, dead and understory) accounted for 36% of Colorado's forest carbon stocks, while belowground carbon (soil and belowground live, dead and understory) comprised 64% of stocks. The largest carbon stock pools were aboveground live and soil, which accounted for 20% and 59% of the stock, respectively (Figure 5; Table 2).

Widespread tree mortality during the reporting period (2002 to 2019) resulted in the aboveground live carbon stocks having the greatest carbon flux (-3.824 ± 0.546 TgC yr^{-1}). Mortality removed 8.483 ± 0.552 TgC yr^{-1} from the aboveground live pool, which far outpaced growth (5.035 ± 0.149 TgC yr^{-1}) and removals (-0.377 ± 0.121 TgC yr^{-1}) and was a major contributor to Colorado's forests acting as a carbon source during this time period. This high mortality-driven reduction in the aboveground and belowground live pools led to gains in the aboveground and belowground dead and down woody material pools. These dead carbon pools had the greatest positive annual fluxes relative to the stock: 4% for aboveground dead, 4% for belowground dead and 2% for down woody material.

4.2 Disturbance and Forest Type Stocks and Fluxes

Disturbances and Cutting

Roughly a third (34%) of Colorado's forestlands remaining forestlands were impacted by disturbance during this study period (Table 3). We summarized stock, fluxes and area of the following disturbance classes: fire, cut, cut and fire (areas where both fire and cutting occurred), insect and disease and weather (i.e., ice, wind, flooding or drought). These disturbed lands were a strong source of carbon, with an annual average net flux of -2.647 ± 0.392 TgC yr^{-1}. The undisturbed lands were a carbon sink, sequestering an average of 0.785 ± 0.230 TgC yr^{-1} (Table 3). Insect and disease impacted the most area (2,547.892 ± 138.200 Kha) in Colorado relative to all other disturbances, accounting for 85% of the total area disturbed and 64% of the disturbance losses (-1.690 ± 0.272 TgC yr^{-1}; Figure 6). Cut areas and burned areas impacted similar area (148.432 ± 42.283 and 203.018 ± 49.482 Kha, respectively) and removed 0.395 ± 0.209 TgC yr^{-1} and -0.535 ± 0.196 TgC yr^{-1}, respectively. Disturbance impacts were greatest on NFS lands, accounting for -2.010 ± 0.351 TgC yr^{-1} of the statewide disturbance flux (Appendix Table 4).

Carbon stocks in Table 3 were calculated using the most recent measurement of plots used in the growth, removal and mortality flux calculations (2012 to 2019) rather than 2010 to 2019 plots used in all other stock estimates in this report. This 2012 to 2019 "re-measurement" stock is calculated only for plots forested at both initial measurement and re-measurement. The re-measurement stocks are used in Table 3 because disturbance information is not retained in the workflow for all plots, just for data used to calculate fluxes, but this could be remedied in future iterations of the inventory. Re-measurement stocks and the 2010 to 2019 stock differ by 3% (Appendix Table 3).

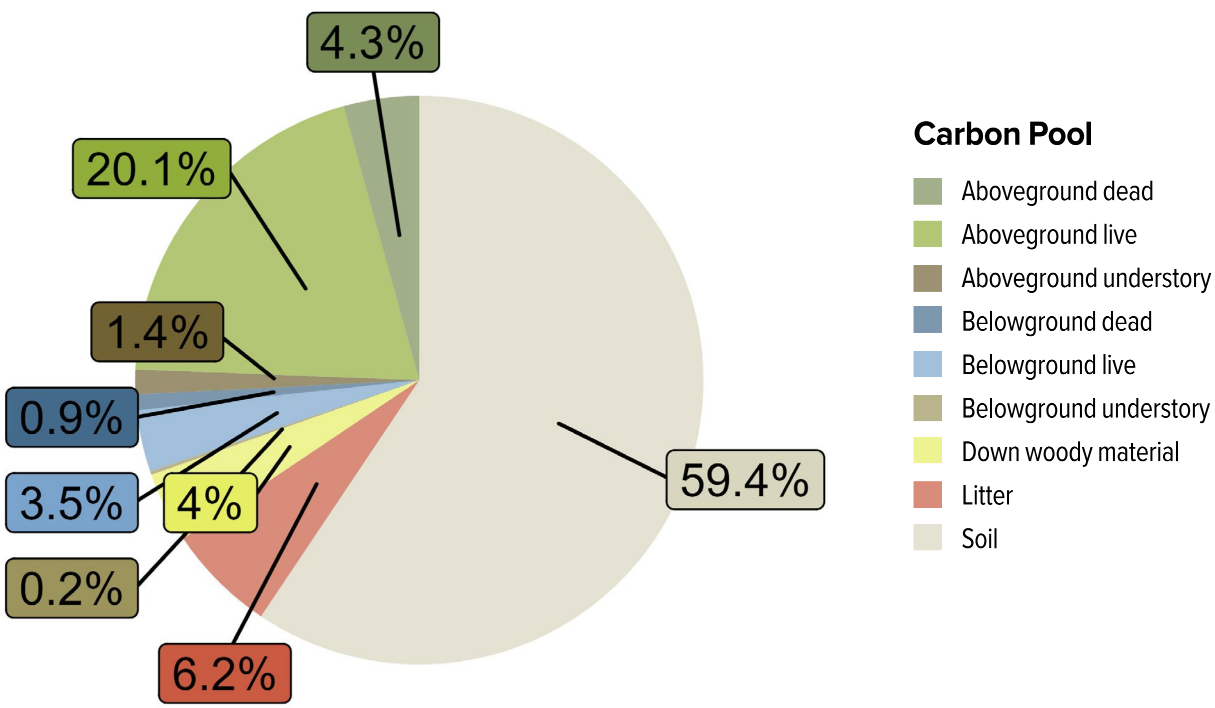


Figure 5. *Statewide carbon stock percentages by carbon pool for forested lands from FIA plots measured between 2010 and 2019.*

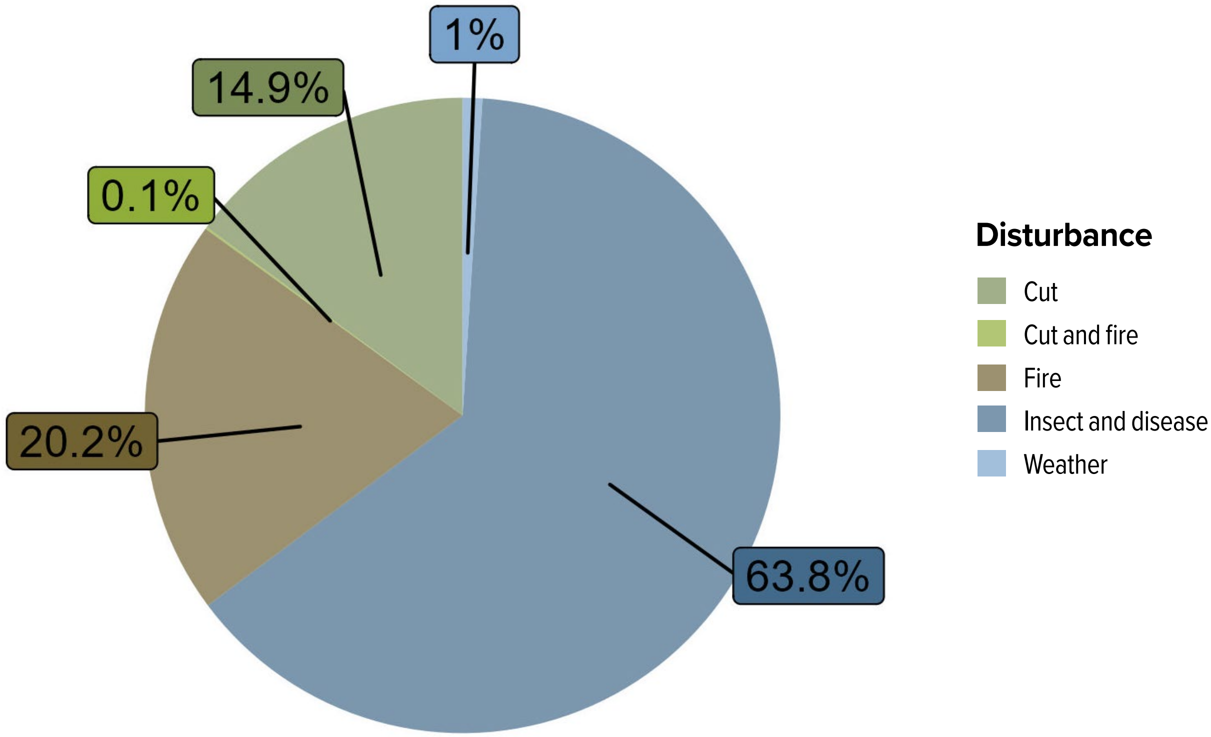


Figure 6. *Statewide carbon flux percentage on disturbed lands by disturbance.*

Table 3. *Stock, average annual net carbon flux (excluding downed woody material), and area of disturbed and undisturbed forest lands in Colorado.*

	Stock*		Flux**		Area	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**
	TgC		*TgC yr⁻¹*		*Kha*	
Cut	24.188	3.640	-0.395	0.106	148.432	21.573
Fire	31.274	4.008	-0.535	0.100	203.018	25.246
Cut and fire	0.323	0.280	-0.002	0.004	2.244	1.901
Insect disease	534.340	15.226	-1.690	0.139	2,547.889	70.510
Weather	13.849	2.765	-0.026	0.021	82.685	15.733
Total disturbed	603.973	15.685	-2.647	0.200	2,984.268	75.721
Undisturbed	996.013	16.725	0.785	0.117	5,817.376	90.345
Total forestland	1,599.986	13.735	-1.863	0.232	8,801.644	72.460

** Stocks for disturbed areas calculated only from 2012 – 2019 plots.*

*** Flux of the down woody material pool is not included in these fluxes.*

We summarized the intensity of each disturbance type by land ownership (Table 4), with intensity defined as the carbon lost from live trees per hectare and year. This live tree carbon moved to other forest carbon pools as trees died and broke down, was partially emitted to the atmosphere from fire combustion or decomposition, or was cut and used in harvested wood products. Fire and insect and disease were the most intense disturbances (Table 4). The intensity of tree mortality on undisturbed lands averaged 2.218 ± 0.162 Mg C ha^{-1} yr^{-1}, which is, unsurprisingly, much lower than disturbed areas.

The average annual loss in aboveground live carbon was most intense on NFS lands (0.801 ± 0.115 Mg C ha^{-1} yr^{-1}), where growth was also highest but was offset by intense mortality and removals (Table 4). The confidence intervals for intensity of live tree carbon loss on state and local government and private lands includes zero, indicating that growth generally balanced removals and harvest on these lands.

Aspen fall color changes depend on tree health, local weather, environmental factors such as drought or increased moisture, elevation, and latitude. ***Photo: Field Peterson, CSFS***

Table 4. *Change in the aboveground (AG) live forest carbon pool through removals and mortality by disturbance class and for undisturbed lands. Gross growth is shown across the combination of disturbed and undisturbed lands. Values are shown by land ownership class.*

	US Forest Service		Other federal		State and local government		Private		All ownerships	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
	Mg C ha^{-1} yr^{-1}									
Harvest										
Removals	-21.107	4.491	-16.236	10.593	-9.440	2.632	-12.168	4.274	-16.577	2.823
Mortality	-10.336	4.262	-1.724	1.724	-6.440	4.585	-1.951	0.957	-6.280	2.185
Cut and fire										
Removals	-11.108	11.108	-*	-*	-*	-*	-4.634	4.634	-8.669	2.461
Mortality	-0.637	0.637	-*	-*	-*	-*	-*	-*	-0.397	0.397
Fire										
Mortality	-34.869	5.565	-16.388	4.809	-30.961	11.108	-17.672	3.907	-27.206	3.497
Insect and disease										
Mortality	-27.007	1.140	-17.314	2.842	-17.342	4.075	-12.200	1.573	-23.349	0.913
Weather										
Mortality	-4.747	1.360	-0.940	0.645	-18.791	18.791	-3.963	2.053	-4.410	1.142
Undisturbed										
Mortality	-2.639	0.108	-1.599	0.239	-1.679	0.340	-1.108	0.128	-2.218	0.083
Gross growth	0.799	0.014	0.257	0.012	0.501	0.049	0.429	0.015	0.572	0.008
Annual AG live flux	-0.801	0.058	-0.129	0.046	-0.162	0.109	-0.031	0.037	-0.435	0.032

** Estimates are not reported for less than 500 acres.*

The high-elevation forest around the Michigan Ditch project area ranges from 8,000-12,900 feet. Approximately 52,000 acres of the site are forested with Engelmann spruce and subalpine fir, lodgepole pine and quaking aspen. ***Photo: Field Peterson, CSFS***

We calculated fire emissions for two greenhouse gases: methane (CH_4) and nitrous oxide (N_20). Together, fires contributed an annual average of -0.105 ± 0.028 $TgCO_2e$ yr^{-1} of CH_4 and N_20 emissions (Table 5). With 71% of the fire flux originating from NFS lands, most of these fire emissions also occurred on NFS lands.

Table 5. *Average annual net wildfire emissions from fire from 2002 to 2009 and 2012 to 2019. CO_2 values are based on Table 3 and were used to calculate methane (CH_4) and nitrous oxide (N_20) emissions.*

	CO_2		CH_4		N_2O		Total CH_4 and N_20	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
				$TgCO_2e$ yr^{-1}				
Fire	-1.962	0.367	-0.063	0.012	-0.041	0.008	-0.104	0.014
Cut and fire	-0.007	0.015	>-0.001	<0.000	>-0.001	<0.000	>-0.001	0.001
Total fire	-1.969	0.367	-0.063	0.012	-0.042	0.008	-0.105	0.014

Forest Type Groups

We calculated the area, stock, flux and carbon density for FIA forest type groups (Table 6). The pinyon/juniper (2,607.810 ± 113.920 Kha), fir/spruce/mountain hemlock (1,922.823 ± 107.410 Kha) and aspen/birch (1,404.885 ± 99.529 Kha) groups covered the most area, accounting for 64% of all forests (Table 6). The fir/spruce/mountain hemlock group had the greatest carbon density (236.088 ± 4.315 Mg ha^{-1}) and stocks (453.956 ± 26.690 TgC). Although the pinyon/juniper group had a low carbon density (120.307 ± 1.635 Mg ha^{-1}) compared to other groups, it held the second most carbon (313.738 ± 14.862 TgC; Figure 7; Table 6) because it covered such an extensive area across Colorado. These two (fir/spruce/hemlock and pinyon/juniper) forest type groups combined held nearly half of Colorado's forest carbon.

Woodlands had a higher percentage of carbon stocks in the modeled soil pool compared to the other forest type groups. For example, the pinyon juniper group had 72% of carbon in soil and 13% in the aboveground live pool (Appendix Table 8). The other forest type groups have nearly twice as much of their carbon stocks in the aboveground live pool (20% - 28%) and 47-60% in the soil pool. The lodgepole pine group and fir/spruce/mountain hemlock group had the greatest percentages of stocks in aboveground dead carbon (7% and 8% of total forest type group stocks, respectively) compared to other forest type groups (Appendix Table 8). While these percentages are similar, the fir/spruce/mountain hemlock forest type group contains 36.302 ± 3.514 TgC in the aboveground dead pool which far exceeds the 8.077 ± 1.627 TgC of aboveground dead carbon in the lodgepole pine group due to the greater area and carbon density of the fir/spruce/mountain hemlock forest type group in Colorado.

When analyzed statewide, only two forest groups had a flux with a 95% confidence interval entirely above zero, indicating high confidence in the forest type groups serving as carbon sinks: ponderosa pine group (0.100 ± 0.080 TgC yr^{-1}) and woodland hardwoods (0.073 ± 0.062 TgC yr^{-1}; Figure 8). The aspen/birch group had the greatest negative net carbon flux (-0.586 ± 0.222 TgC yr^{-1}; Figure 8; Table 6). However, the carbon stocks and average fluxes for any given forest type group varied substantially across the four Colorado State Forest Service (CSFS) areas (Figure 2; Table 7; Table 8). For example, the pinyon/juniper group was a weak carbon sink in the Northwest CSFS area (0.027 ± 0.026 TgC yr^{-1}), but a moderate source of carbon in the Southwest area (-0.117 ± 0.042 TgC yr^{-1}). The fir/spruce/hemlock group was a strong carbon source in the Southwest CSFS area (-0.333 ± 0.165 TgC yr^{-1}), presumably due to widespread and severe spruce beetle outbreaks, and a carbon sink in the Southeast area (0.063 ± 0.048 TgC yr^{-1}). The ponderosa pine group is the only group to have a positive flux across all areas, although the confidence interval spans zero in three of the four areas. Statewide, the fir/spruce/mountain hemlock, aspen/birch and lodgepole pine groups had the greatest loss in the aboveground live pool due to high mortality fluxes in both of these forest type groups (Appendix Table 9).

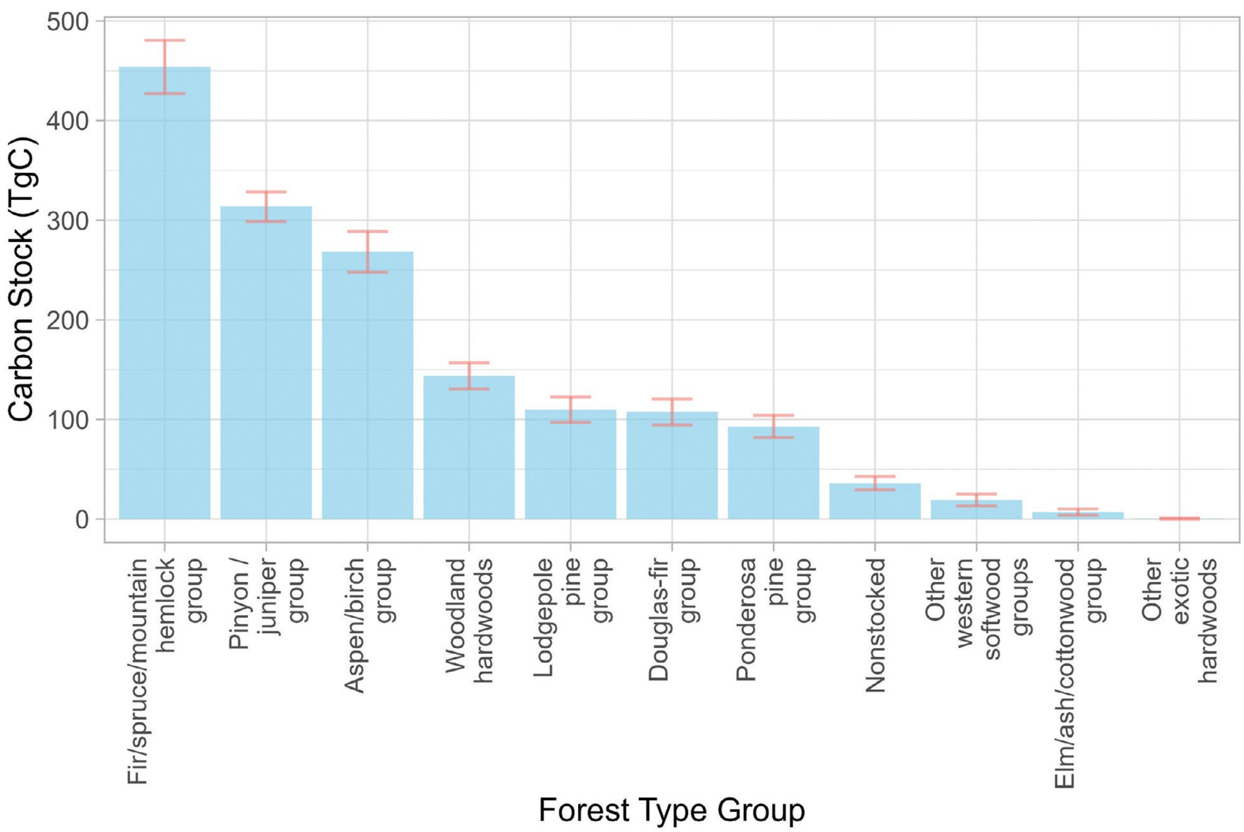


Figure 7. *Carbon stock by FIA forest type group for forested lands from FIA plots measured between 2010 and 2019. 95% confidence intervals are shown in red.*

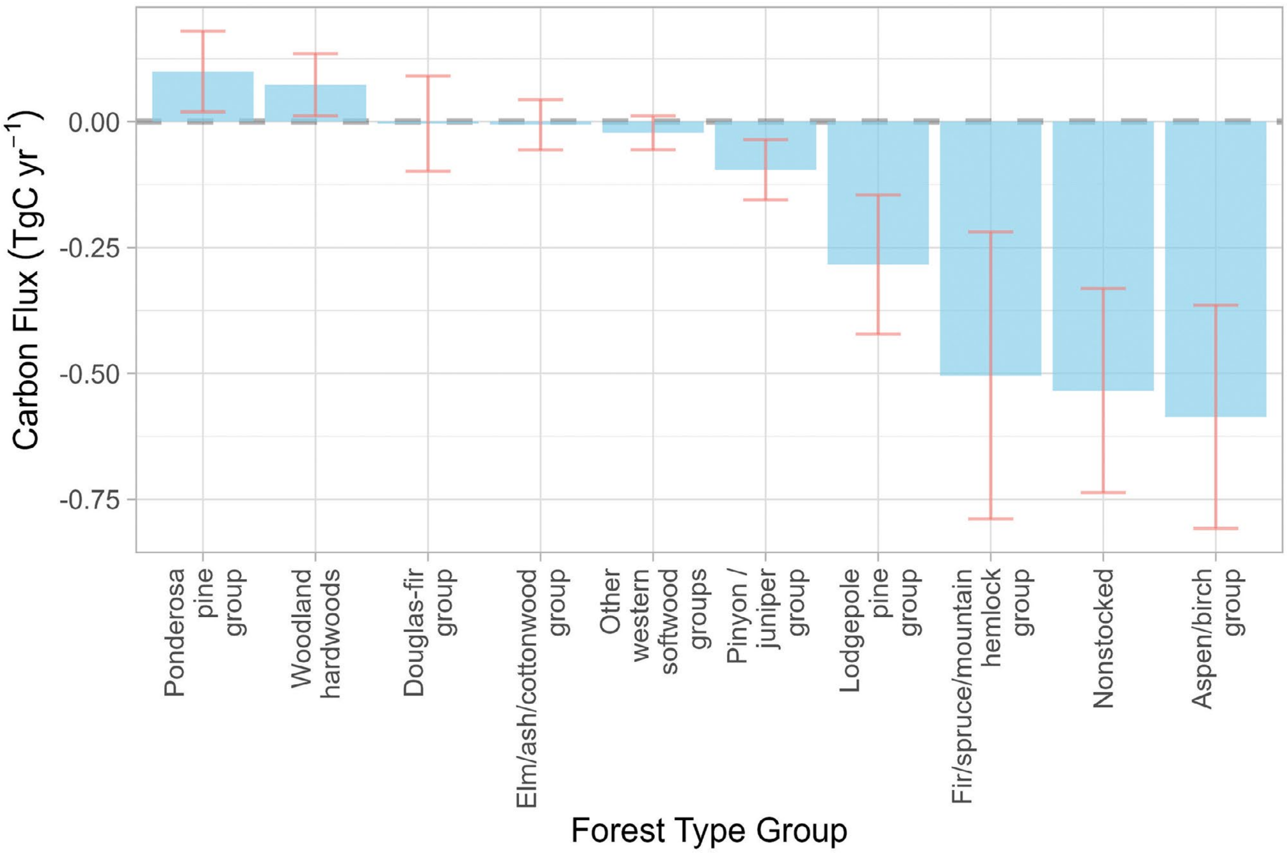


Figure 8. *Average annual net carbon flux by FIA forest type group for forested lands remaining forested from FIA plots measured between 2002 to 2009 and 2012 to 2019. These fluxes do not include down woody material. 95% confidence intervals are shown in red.*

Table 6. *Carbon stock, average annual net carbon flux (excluding downed woody material), area and carbon density for FIA forest type groups.*

	Stock		Flux*		Area		Carbon density	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
	TgC		*TgC yr⁻¹*		*Kha*		*Mg C ha⁻¹*	
Pinyon / juniper group	313.738	7.583	-0.095	0.030	2,607.810	58.122	120.307	0.834
Douglas-fir group	107.484	6.560	-0.004	0.048	613.745	35.422	175.128	2.539
Ponderosa pine group	92.963	5.748	0.100	0.041	577.427	33.567	160.994	2.459
Fir/spruce/mountain hemlock group	453.956	13.617	-0.504	0.145	1,922.823	54.801	236.088	2.201
Lodgepole pine group	109.696	6.550	-0.284	0.070	572.348	32.789	191.659	2.860
Other western softwood groups	19.166	2.927	-0.022	0.017	109.381	15.613	175.218	6.627
Elm/ash/cottonwood group	6.986	1.622	-0.006	0.026	45.458	9.817	153.674	9.940
Aspen/birch group	268.310	10.419	-0.586	0.113	1,404.885	50.780	190.983	2.305
Woodland hardwoods	143.733	6.636	0.073	0.032	1,028.393	44.703	139.765	1.518
Other exotic hardwoods	0.540	0.366	-**	-**	5.403	3.627	99.858	3.098
Nonstocked	36.027	3.346	-0.534	0.103	322.539	25.428	111.698	3.842
Total	1,552.597	12.006	-1.863	0.232	9,210.213	60.975	168.573	0.849

** Flux of the down woody material pool is not included in these fluxes.*

*** Estimates are not reported for less than 500 acres.*

Table 7. *Carbon stocks by FIA forest type group for the Colorado State Forest Service (CSFS) areas.*

	CSFS Areas							
	Northwest		Northeast		Southwest		Southeast	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC							
Pinyon / juniper group	127.652	4.777	3.706	1.183	106.883	4.533	75.497	3.569
Douglas-fir group	18.942	2.928	20.399	2.676	41.782	4.182	26.361	3.132
Ponderosa pine group	2.316	1.022	29.440	3.014	36.994	3.900	24.213	2.775
Fir/spruce/mountain hemlock group	182.757	8.400	29.025	3.871	205.983	9.220	36.192	3.858
Lodgepole pine group	37.024	4.152	34.069	3.339	31.212	3.439	7.390	1.639
Other western softwood groups	-**	-**	4.378	1.505	6.915	1.681	7.872	1.865
Elm/ash/cottonwood group	1.613	0.792	1.959	0.869	2.195	0.892	1.218	0.673
Aspen/birch group	131.026	7.157	5.411	1.381	115.017	6.965	16.856	2.629
Woodland hardwoods	67.368	4.495	5.456	1.042	52.842	4.116	18.067	2.410
Other exotic hardwoods	-**	-**	-**	-**	-**	-**	0.540	0.366
Nonstocked	14.084	1.974	7.411	1.425	10.924	2.090	3.609	0.949
Total	582.782	7.408	141.253	3.532	610.747	7.577	217.814	4.404

*** Estimates are not reported for less than 500 acres.*

Table 8. *Average annual net carbon fluxes (excluding downed woody material) by FIA forest type group for the Colorado State Forest Service (CSFS) areas.*

	CSFS Areas							
	Northwest		Northeast		Southwest		Southeast	
	Total	SE	Total	SE	Total	SE	Total	SE
	$TgC\ yr^{-1}$							
Pinyon / juniper group	0.027	0.013	-0.001	0.004	-0.117	0.022	-0.005	0.017
Douglas-fir group	0.047	0.018	0.016	0.016	-0.058	0.036	-0.009	0.021
Ponderosa pine group	0.009	0.006	0.017	0.026	0.061	0.026	0.012	0.016
Fir/spruce/mountain hemlock group	-0.205	0.112	-0.029	0.031	-0.333	0.084	0.063	0.025
Lodgepole pine group	-0.275	0.061	-0.081	0.031	0.066	0.015	0.006	0.009
Other western softwood groups	-**	-**	-0.004	0.004	-0.022	0.016	0.004	0.005
Elm/ash/cottonwood group	-0.026	0.023	0.005	0.004	0.014	0.007	0.000	0.007
Aspen/birch group	-0.409	0.084	0.017	0.012	-0.141	0.065	-0.053	0.039
Woodland hardwoods	0.066	0.021	0.007	0.006	0.014	0.016	-0.014	0.017
Other exotic hardwoods	-**	-**	-**	-**	-**	-**	-**	-**
Nonstocked	-0.183	0.046	-0.066	0.025	-0.219	0.083	-0.066	0.033
Total	-0.949	0.160	-0.118	0.060	-0.734	0.141	-0.062	0.070

Flux of the down woody material pool is not included in these fluxes.

*** Estimates are not reported for less than 500 acres.*

4.3 Regional and Ownership Forest Carbon Stocks and Fluxes

Here we present carbon stocks and fluxes by administrative boundaries. The forest ecosystem results can be disaggregated into greater detail to show disturbance, GRM, pool, forest type and more by each of these regional and ownership categories. Appendix C shows some of this more detailed information and illustrates the types of data summarizations that can be generated from this inventory.

Trends by Ownership

The U.S. Forest Service is the largest forest landowner (48%) in Colorado, followed by private (26%), other federal (23%) and state and local government (3%; Table 9). The National Forest System (NFS) forested lands also hold the largest carbon stock (879.655 ± 24.904 TgC: 57% of total stocks) followed by private (342.301 ± 14.665 TgC; 22%), other federal (283.913 ± 15.803 TgC; 18%) and state and local government (46.728 ± 8.343 TgC; 3%; Table 10).

Table 9. *Area of forested land in Colorado by land ownership, as measured by 2010 to 2019 FIA plots.*

	Ownership group								All ownerships	
	US Forest Service		Other federal		State and local government		Private			
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
Forested *(Th ac)*	10,802	144	5,240	130	791	67	5,925	109	22,759	151
Forested *(Kha)*	4,372	58	2,121	52	320	27	2,398	44	9,210	61

Table 10. *Forest carbon pool stocks by land ownership for forested FIA plots measured from 2010 to 2019.*

	Ownership group								All ownerships	
	US Forest Service		Other federal		State and local government		Private			
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	TgC									
Aboveground live	205.259	3.993	40.585	1.698	8.070	0.931	57.703	1.932	311.617	4.045
Aboveground dead	54.101	1.878	6.777	0.726	1.151	0.276	4.986	0.434	67.015	1.959
Belowground live	33.778	0.670	8.178	0.314	1.361	0.154	10.412	0.336	53.728	0.689
Belowground dead	11.500	0.394	1.475	0.150	0.251	0.060	1.067	0.086	14.293	0.409
Down woody material	41.435	1.055	9.962	0.494	1.406	0.202	9.517	0.403	62.320	1.124
Litter	60.057	0.905	14.817	0.489	2.652	0.263	18.790	0.462	96.316	0.840
Aboveground understory	9.253	0.189	5.579	0.148	0.840	0.080	6.392	0.147	22.064	0.239
Belowground understory	1.028	0.021	0.620	0.016	0.093	0.009	0.710	0.016	2.452	0.027
Soil	463.243	7.134	195.920	5.402	30.904	2.797	232.725	5.218	922.792	7.855
Total	879.655	12.706	283.913	8.063	46.728	4.256	342.301	7.482	1,552.597	12.006

National Forest System forested lands had the largest average annual net loss (-0.608 TgC yr^{-1}; Table 11), comprising 70% of the total flux with DWM from all ownerships (-0.867 TgC yr^{-1}). Private land had the next highest net carbon losses (-0.183 TgC yr^{-1}; 21%) followed by state and local government land (-0.046 TgC yr^{-1}; 5%) and then other federal lands (-0.030 TgC yr^{-1}; 3%). The proportion of the state's forest carbon losses on other federal lands (3%) was disproportionately lower than the proportion of the state's forest area it comprises (23%).

Table 11. *Average annual net changes in carbon pools and annual average growth, removals, and mortality by land ownership for forested lands remaining forested from FIA plots measured between 2002 to 2009 and 2012 to 2019.*

	Ownership group									
	US Forest Service		Other federal		State and local government		Private		All ownerships	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	TgC yr^{-1}									
Aboveground live flux	-3.441	0.255	-0.265	0.095	-0.052	0.035	-0.066	0.078	-3.824	0.279
Growth	3.435	0.075	0.531	0.030	0.160	0.022	0.909	0.039	5.035	0.076
Removal	-0.193	0.046	-0.025	0.018	-0.012	0.007	-0.147	0.037	-0.377	0.062
Mortality	-6.683	0.264	-0.772	0.106	-0.200	0.043	-0.828	0.078	-8.483	0.282
Aboveground dead	2.338	0.182	0.248	0.075	0.026	0.026	0.052	0.046	2.664	0.200
Belowground live	-0.617	0.044	-0.220	0.018	-0.020	0.007	-0.099	0.014	-0.956	0.048
Belowground dead	0.493	0.037	0.054	0.015	0.007	0.005	0.013	0.009	0.567	0.040
Down woody material *	0.905	0.373	0.170	0.185	-0.008	0.023	-0.072	0.083	0.995	0.425
Litter	-0.379	0.030	-0.044	0.012	-0.006	0.005	-0.007	0.011	-0.436	0.034
Aboveground understory	0.069	0.009	0.007	0.003	0.003	0.002	-0.002	0.005	0.078	0.011
Belowground understory	0.008	0.001	0.001	<0.001	<0.001	<0.001	>-0.001	0.001	0.009	0.001
Soil	0.015	0.040	0.020	0.014	0.003	0.015	-0.002	0.019	0.036	0.048
Total without down woody material	-1.514	0.206	-0.200	0.064	-0.038	0.040	-0.111	0.083	-1.863	0.232
Total **	-0.608	-	-0.030	-	-0.046	-	-0.183	-	-0.867	-

** Flux of the down woody material pool is calculated from a subset of plots.*

*** Standard error not reported for total with down woody material.*

Trend by County and Colorado State Forest Service Areas

The western half of Colorado contains more forested land than eastern Colorado, which is reflected in the higher carbon stocks in the Northwest (582.782 ± 14.520 TgC; 38% of total stocks) and Southwest (610.747 ± 14.851 TgC; 39%) CSFS areas as compared to the Northeast (141.253 ± 6.923 TgC; 9%) and Southeast (217.814 ± 8.631 TgC; 14%) CSFS areas (Figure 9; Table 12). Out of the top ten counties with the highest carbon stocks, six are in the Northwest (Mesa, Garfield, Rio Blanco, Routt, Grand, Eagle), three are in the Southwest (Gunnison, Saguache, Montrose) and one is in the Northeast (Larimer). The Northwest and Southwest areas were carbon sources, with the Northwest area being the largest source (-0.949 ± 0.313 TgC yr^{-1}). The Northeast (-0.118 ± 0.118 TgC yr^{-1}) and Southeast (-0.062 ± 0.137 TgC yr^{-1}) regional changes were near zero, with confidence intervals indicating these regions could either be weak sources or sinks. Five counties in Colorado were carbon sinks, 15 were carbon sources, 15 had too little data or forest land to estimate flux and 29 counties had confidence intervals spanning a flux of zero (Figure 9; Table 12).

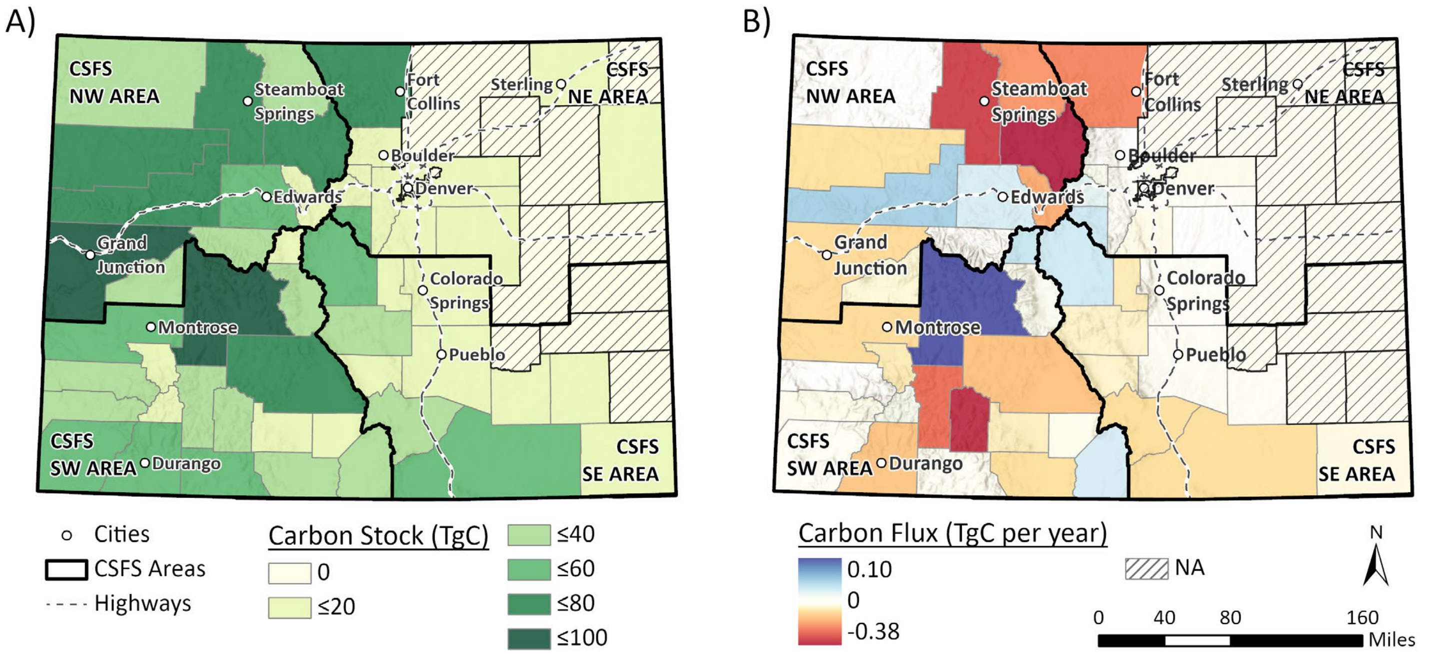


Figure 9. *A) Carbon stock of Colorado counties for forested lands from FIA plots measured between 2010 and 2019. B) The average annual net flux is shown for Colorado's forest lands remaining forested for plots measured between 2002 to 2009 and 2012 to 2019.*

Table 12. *Carbon stock, average annual net carbon flux, and area by Colorado counties (grouped by CSFS areas).*

Counties in CSFS areas	Stock		Flux*		Forest area		Carbon density	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC		*TgC yr⁻¹*		*Kha*		*Mg ha⁻¹*	
Northwest area								
Delta	24.433	1.619	-0.010	0.029	138.694	8.558	176.164	7.460
Eagle	58.525	2.336	0.033	0.027	290.220	9.413	201.656	5.652
Garfield	79.965	2.660	0.056	0.039	484.324	11.673	165.107	3.913
Grand	60.586	1.940	-0.384	0.060	294.151	8.528	205.967	4.367
Jackson	33.970	1.957	-0.153	0.047	176.363	9.572	192.614	6.001
Mesa	80.321	2.946	-0.041	0.044	527.758	16.492	152.192	3.554
Moffat	37.403	1.979	0.005	0.017	311.450	13.443	120.093	3.806
Pitkin	37.135	1.954	0.005	0.062	162.588	7.856	228.401	8.884
Rio Blanco	76.162	2.973	-0.029	0.032	511.843	16.396	148.799	3.623
Routt	74.372	2.447	-0.312	0.088	376.499	10.552	197.537	4.060
Summit	19.911	0.945	-0.119	0.043	93.595	5.270	212.738	7.868
Northwest area total	582.782	7.408	-0.949	0.160	3,367.486	37.213	173.062	1.456

Counties in CSFS areas	Stock		Flux *		Forest area		Carbon density	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC		*TgC yr⁻¹*		*Kha*		*Mg ha⁻¹*	
Northeast area								
Adams	0.016	0.016	-0.001	0.001	0.588	0.588	26.592	26.592
Arapahoe	0.442	0.442	0.002	0.002	2.318	2.318	190.907	190.907
Boulder	16.469	1.507	0.006	0.022	90.181	6.768	182.619	8.389
Broomfield	- **	- **	- **	- **	- **	- **	- **	- **
Clear Creek	14.832	1.184	0.025	0.010	71.745	4.619	206.730	12.027
Denver	- **	- **	- **	- **	- **	- **	- **	- **
Douglas	15.300	1.187	-0.004	0.019	102.576	6.175	149.157	5.556
Elbert	2.141	0.906	0.005	0.003	13.157	5.242	162.714	15.300
Gilpin	7.609	0.612	0.014	0.007	37.526	1.390	202.760	11.777
Jefferson	18.638	1.313	0.009	0.017	117.259	8.297	158.946	5.100
Kit Carson	- **	- **	- **	- **	- **	- **	- **	- **
Larimer	65.022	2.002	-0.174	0.048	354.547	9.500	183.394	3.925
Lincoln	- **	- **	- **	- **	- **	- **	- **	- **
Logan	0.573	0.474	- **	- **	3.751	3.098	152.891	152.891
Morgan	- **	- **	- **	- **	- **	- **	- **	- **
Phillips	- **	- **	- **	- **	- **	- **	- **	- **
Sedgwick	- **	- **	- **	- **	- **	- **	- **	- **
Washington	- **	- **	- **	- **	- **	- **	- **	- **
Weld	- **	- **	- **	- **	- **	- **	- **	- **
Yuma	0.212	0.212	- **	- **	1.791	1.791	118.308	118.308
Northeast area total	141.253	3.532	-0.118	0.060	795.437	17.673	177.579	2.584

Counties in CSFS areas	Stock		Flux *		Forest area		Carbon density	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC		*TgC yr⁻¹*		*Kha*		*Mg ha⁻¹*	
Southwest area								
Alamosa	2.083	0.876	-0.001	0.002	11.921	4.819	174.754	19.395
Archuleta	50.765	2.090	-0.117	0.044	278.650	9.481	182.183	5.472
Chaffee	26.510	1.358	0.015	0.021	160.398	6.522	165.278	5.524
Conejos	22.877	1.603	-0.031	0.030	109.368	7.362	209.176	9.953
Costilla	20.461	1.178	0.035	0.015	117.075	4.390	174.766	7.066
Dolores	30.916	1.873	-0.002	0.018	158.969	9.266	194.482	8.000
Gunnison	99.135	2.852	0.102	0.040	491.932	11.202	201.521	4.650
Hinsdale	34.057	2.229	-0.218	0.063	159.381	8.130	213.684	8.617
Lake	9.238	1.079	0.043	0.008	53.288	5.529	173.359	11.194
La Plata	47.839	1.933	-0.080	0.028	311.064	8.632	153.791	4.985
Mineral	29.982	1.938	-0.345	0.079	147.489	7.625	203.280	8.592
Montezuma	42.069	1.656	0.001	0.027	294.313	9.794	142.938	3.948
Montrose	54.823	2.120	-0.040	0.020	385.914	12.304	142.061	3.225
Ouray	15.805	1.329	-0.018	0.015	85.676	5.572	184.473	13.016
Rio Grande	19.625	1.253	-0.017	0.017	105.623	5.736	185.805	8.989
Saguache	64.229	1.877	-0.086	0.040	371.568	9.262	172.860	3.087
San Juan	8.436	0.997	0.019	0.010	43.233	4.386	195.129	10.798
San Miguel	31.896	2.474	0.005	0.018	187.539	12.688	170.075	7.312
Southwest area total	610.747	7.577	-0.734	0.141	3,473.400	35.314	175.835	1.491

Counties in CSFS areas	Stock		Flux *		Forest area		Carbon density	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC		*TgC yr⁻¹*		*Kha*		*Mg ha⁻¹*	
Southeast area								
Baca	1.183	0.581	-0.005	0.005	10.878	5.022	108.776	13.107
Bent	1.898	0.455	<0.001	<0.001	21.724	4.578	87.353	5.170
Cheyenne	- **	- **	- **	- **	- **	- **	- **	- **
Custer	17.400	1.472	-0.013	0.029	97.852	5.800	177.819	8.997
Crowley	- **	- **	- **	- **	- **	- **	- **	- **
El Paso	12.185	0.993	0.011	0.008	85.471	6.715	142.562	5.864
Fremont	38.702	1.466	-0.013	0.019	282.957	8.448	136.778	3.158
Huerfano	26.790	1.484	-0.033	0.035	191.036	7.934	140.234	4.512
Kiowa	- **	- **	- **	- **	- **	- **	- **	- **
Las Aminas	48.486	2.143	-0.033	0.033	410.920	16.219	117.994	2.531
Otero	1.174	0.514	0.002	0.002	12.525	5.219	93.748	6.575
Park	43.037	1.625	0.038	0.032	267.319	8.162	160.997	3.464
Pueblo	9.968	1.429	0.001	0.003	83.356	10.131	119.583	6.245
Prowers	- **	- **	- **	- **	- **	- **	- **	- **
Teller	16.991	1.344	-0.018	0.018	109.852	7.414	154.671	5.755
Southeast area total	217.814	4.404	-0.062	0.070	1,573.890	27.816	138.392	1.507

** Flux of the down woody material pool is not included in these fluxes.*

*** Estimates are not reported for less than 500 acres.*

Trends by National Forest

With nearly half (48%) of the state's forested area being NFS land, here we present forest carbon stocks and fluxes by national forest. Eight national forests manage forest land in Colorado, although some of these cross state boundaries and only partially fall in Colorado (i.e., Medicine Bow-Routt National Forests and Manti-La Sal National Forest). Results represent carbon on the Colorado portions of these national forests that cross state lines. The Grand Mesa-Uncompahgre-Gunnison National Forests has the largest carbon stock (185.459 ± 13.079 TgC; Figure 10; Appendix Table 6), which accounts for 12% of statewide stocks and 21% of NFS stocks. Four of the national forests are carbon sources and four have a flux near zero (Figure 11; Appendix Table 7).

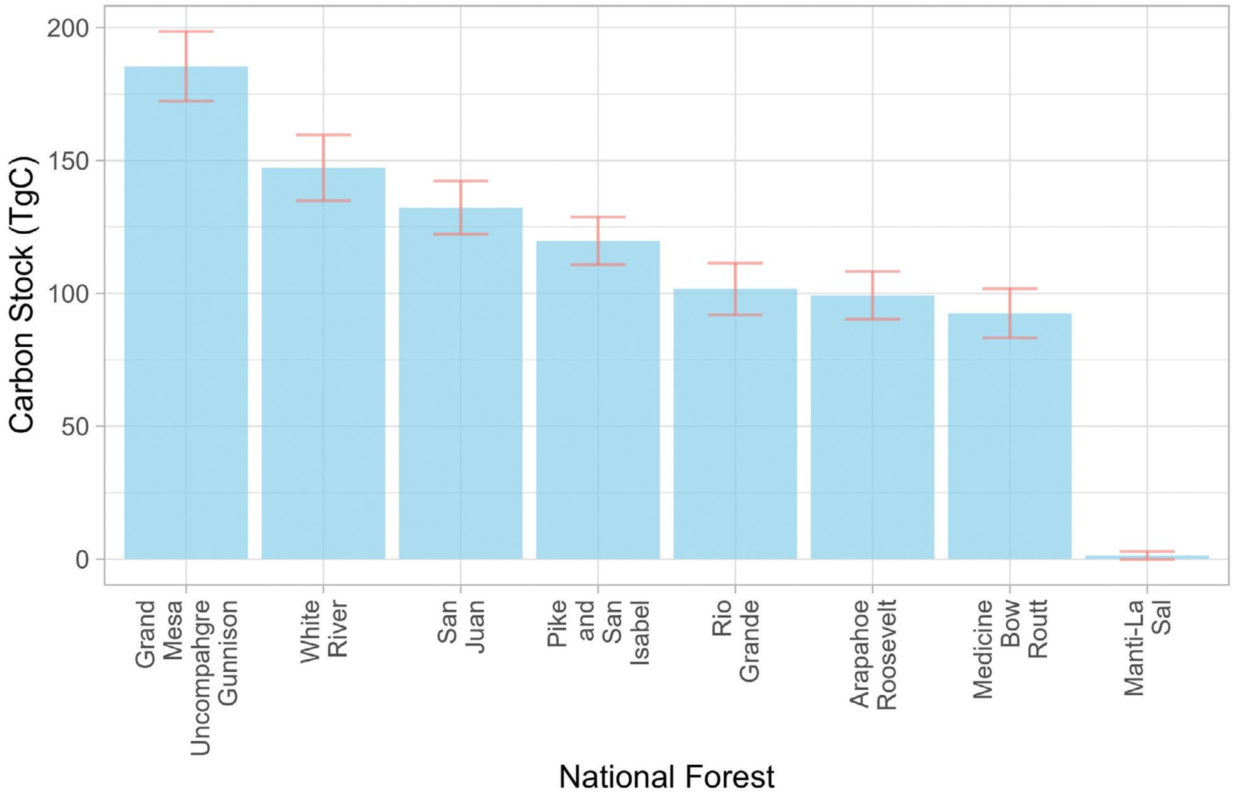


Figure 10. *Carbon stock by National Forest from FIA plots measured between 2010 and 2019. 95% confidence intervals are shown in red. For national forests that cross state lines (i.e., Manti-La Sal National Forest and Medicine Bow-Routt National Forests), estimates are only for parts of national forests that fall in Colorado.*

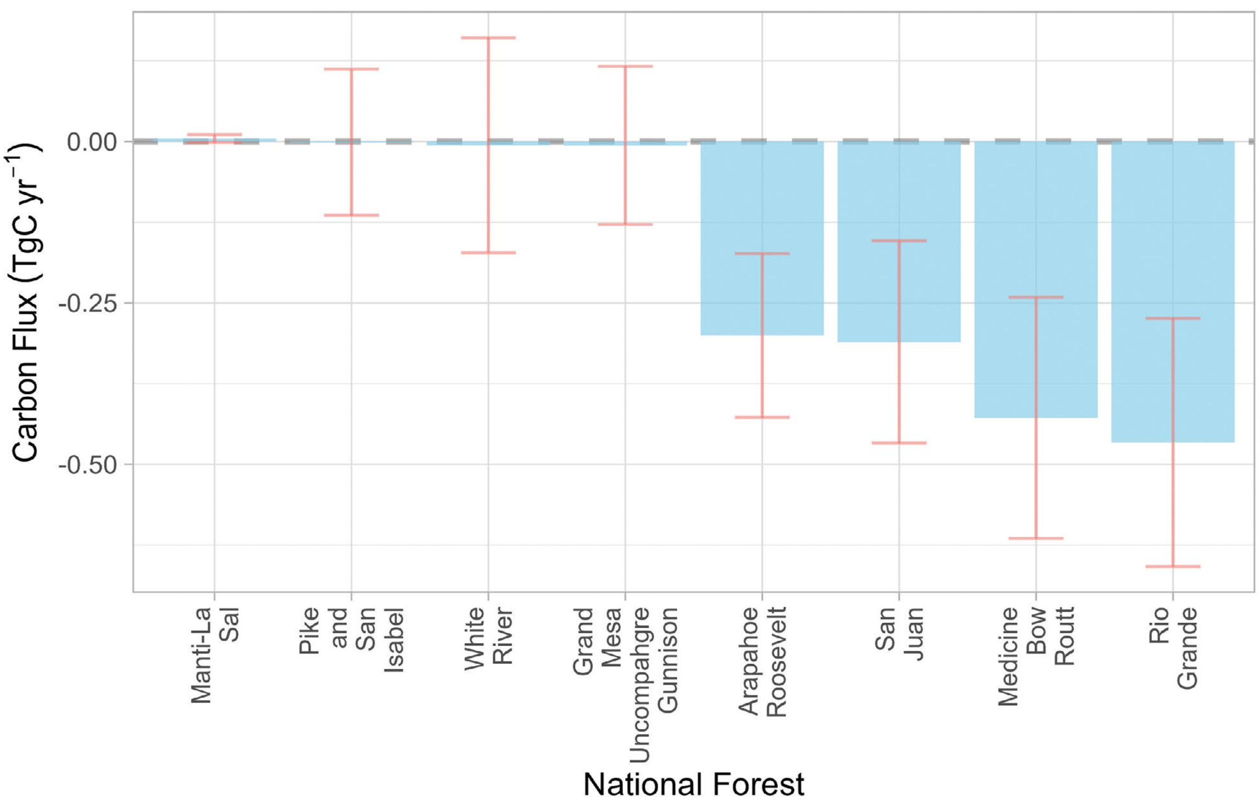


Figure 11. *Average annual net carbon flux by National Forest for forested lands remaining forested from FIA plots measured between 2002 to 2009 and 2012 to 2019. These fluxes do not include down woody material. 95% confidence intervals are shown in red. For national forests that cross state lines (i.e., Manti-La Sal National Forest and Medicine Bow-Routt National Forests), estimates are only for parts of national forests that fall in Colorado.*

5 HARVESTED WOOD PRODUCTS CARBON RESULTS

In this section, we report the harvested wood products model results of the total carbon held in different harvested wood products storage pools, which include Products in Use (PIU) and products in Solid Waste Disposal Sites (SWDS). Stocks presented in this section represent the cumulative total carbon held in each pool at a given time while fluxes represent the annual change in carbon stocks using the IPCC production approach, or the difference between additions (harvest) and emissions using the simple-decay approach. For PIU changes, it is important to note that negative numbers do not represent emissions, but instead a loss of PIU carbon stock from the preceding year due to less new product entering the pool from harvest versus leaving it through disposal. For SWDS and net changes for both pools combined, negative numbers do represent emissions as more carbon is lost through decay than enters storage pools. We report timber harvest numbers in the year they occurred (1954 to 2019), but in the model this timber moves into harvested wood products pools the year following harvest, so we report stocks and fluxes one year after harvest (1955 to 2020).

5.1 Total State Timber Harvest

From 1954 to 2019, a total of 15.316 TgC (9.9 million MBF) was harvested across all ownerships in Colorado (Figure 12). The annual average harvest from 1954 to 2019 was 0.232 TgC yr^{-1} (149,677 MBF yr^{-1}; Supplemental File S2). Harvested material remained above 0.250 TgC yr^{-1} from 1954 to 1979, however, after 1979 average annual harvest declined roughly 50% across Colorado and has not rebounded to 1954 to 1979 levels since (Figure 13). On average, annual harvests between 1954 to 1979 were 0.336 TgC yr^{-1}, while average annual harvest between 1980 to 2019 was 0.164 TgC yr^{-1}. The highest reported harvesting occurred in 1968, where a total of 0.476 TgC was harvested across all ownerships, while the lowest harvest levels occurred in 2003 with 0.112 TgC harvested. Given that removals in the forest ecosystem model average 0.377 TgC yr^{-1}, our average estimate of harvested material transported to mills for this same 2002 to 2019 period of 0.144 TgC yr^{-1} is reasonable as not all material cut is transported to mills.

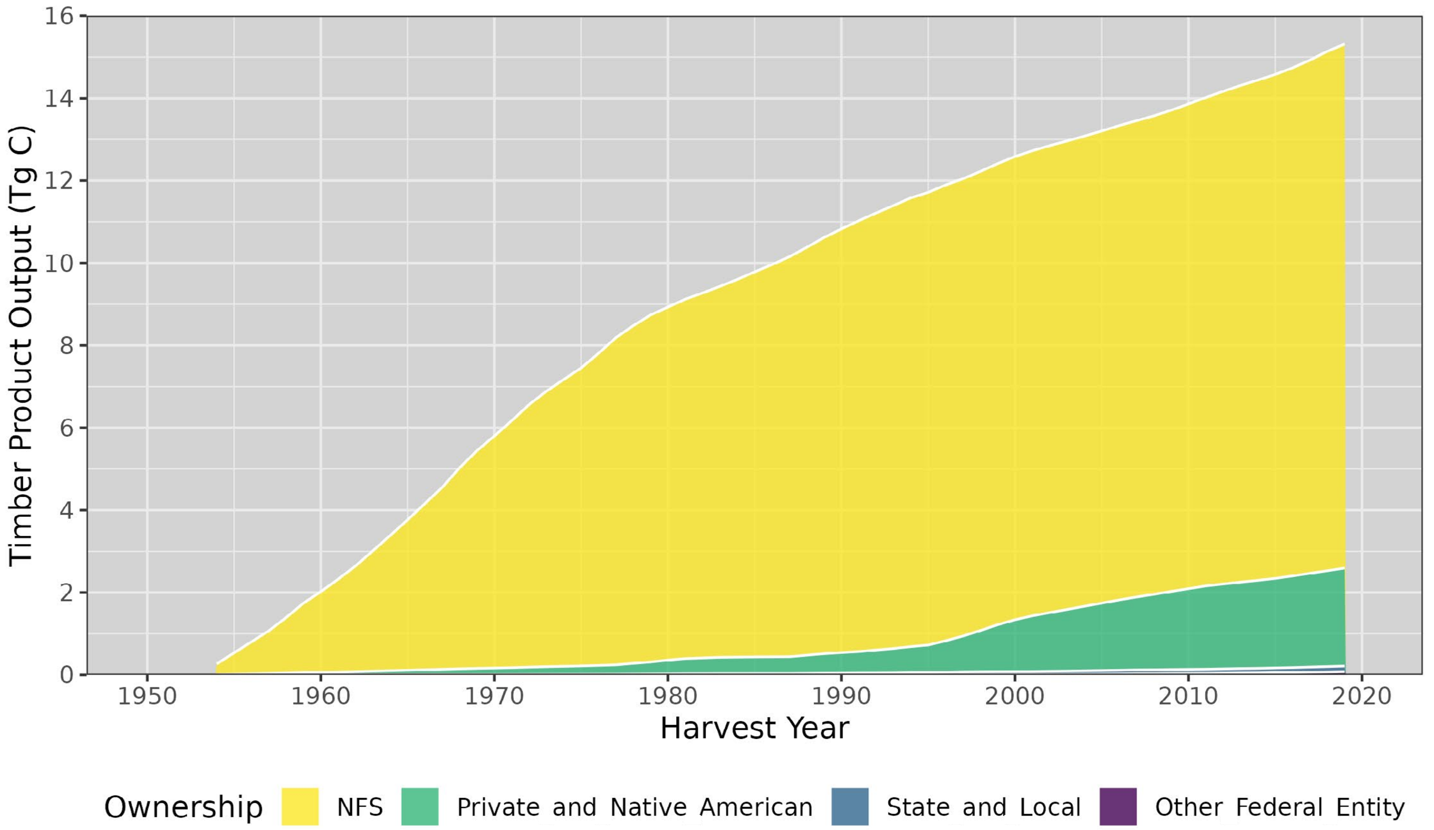


Figure 12. *Cumulative Colorado timber product output from 1954 to 2019 across National Forest Service (NFS), Private and Native American, State and Local and Other Feder Entity land ownerships.*

The majority of timber products in Colorado originated from NFS lands between 1954 and 2019. National Forest System lands accounted for roughly 97% of annual harvests from 1954 to 1977 in our dataset, with the other 3% from Private and Native American and State and Local lands. Starting in 1978, NFS representation in harvests vacillated between accounting for 23% in 1997 to 98% in 1987 of annual timber harvests in the state (Figure 13). Over the entire study period, NFS lands accounted for 76% of annual harvests in Colorado. Harvests are not reported from other federal entities until 1993, where they account for an average of 1% of the annual harvests from 1993 to 2019. Over the 1954 to2019 period, other federal entities on average account for less than 1% of the total annual harvest. Starting in 1978, private and Native American lands began to account for a greater percentage of harvests, varying from a low of 1% in 1988 to a high of 74% in 1999 (Figure 13). Considering the average annual harvest cumulatively between 1954 to 2019, private and Native American lands accounted for 22% of annual harvests in Colorado. State and local lands accounted for less that 1% of the total annual harvest between 1954 and 1977. They accounted for approximately 2% of the annual harvest from 1978 to 2019. Over the entire study period, state and local lands accounted for about 1% of the total annual harvest in Colorado. State and local lands varied between a low of less than 1% across multiple years within the study timeline to a high of 4% in 1995 (Figure 13).

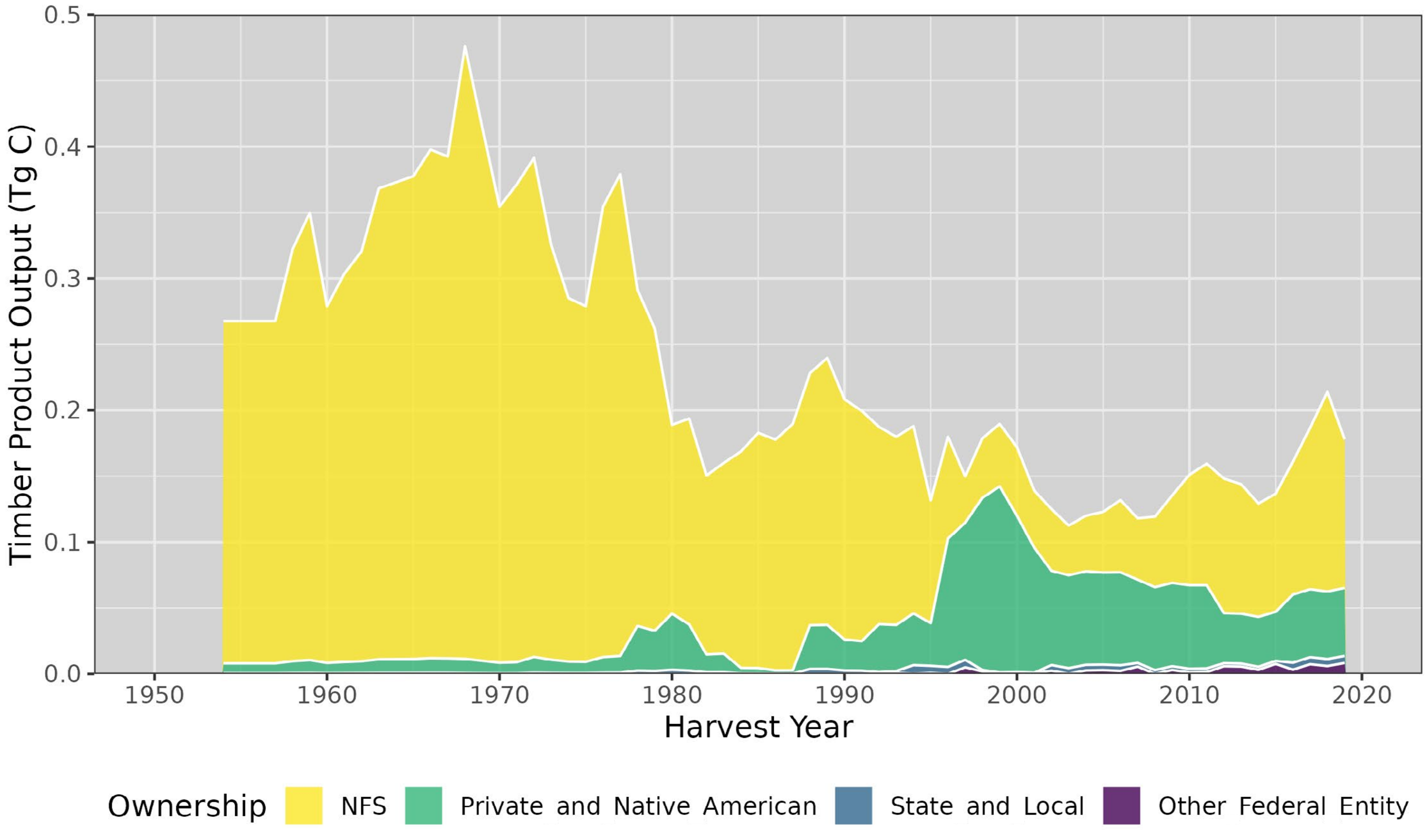


Figure 13. *Colorado timber product output by ownership from 1954 to 2019.*

5.2 Harvested Wood Products Carbon Stocks

Carbon stored in harvested wood products as of 2020 was 5.805 TgC. A Monte Carlo analysis was run to quantify the modeling error of the harvested wood products stocks. The Monte Carlo simulated mean was 5.809 TgC, with the 90% confidence interval ranging from 4.749 TgC to 6.821 TgC (Figure 14; Supplemental File S2).

Carbon in SWDS accounts for 2.653 TgC (46%) of the 2020 stock, while PIU accounts for 3.153 TgC (54%). Over the entire study period (1955 to 2020), average stocks in both SWDS and PIU were 3.893 TgC, with PIU accounting for 2.507 TgC and SWDS stocks accounting for 1.386 TgC (Figure 14). For the period of 2011 to 2020 (coincident with the forest ecosystem stock measurement period), average carbon stocks in harvested wood products were 5.541 TgC, with 3.058 TgC (55%) in PIU and 2.483 TgC (45%) in SWDS.

While 5.805 TgC of the harvested wood from 1954 to 2019 was still being stored as wood products as of 2020 (Figure 14), 9.511 TgC has been emitted with and without energy capture. Emissions with energy capture account for 64% of the emissions and emissions without energy capture account for 36%.

A log deck at a forest management site, with these trees removed to reduce the spread of insect outbreaks in the area.
Photo: Field Peterson, CSFS

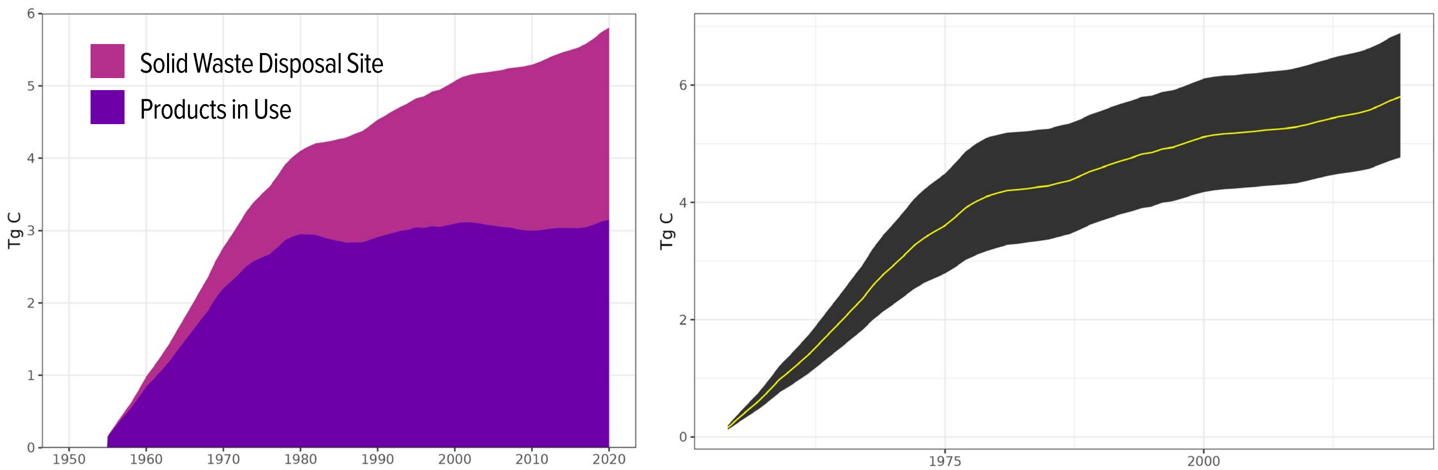


Figure 14. *(Left) Carbon stored in harvested wood products by pool from 1955 to 2020. (Right) Monte Carlo mean and 90% confidence intervals for harvested wood products total carbon stocks (products in use and products in solid waste disposal sites).*

In terms of stocks over time, the period from 1954 to 1978 saw the sharpest increase in total carbon stored in harvested wood products while after 1978 total carbon stocks maintained an increase albeit at a decreased rate (Figure 14). The continued increase was largely due to an increase in the amount of carbon stored in SWDS between 1978 to 2020 as harvested wood products from historic harvests were retired, while PIU total carbon stocks maintained a relatively flat carbon stock during this time period and even decreased at times (discussed in section 5.3).

5.3 Harvested Wood Products Carbon Fluxes

Harvested wood products have served as a carbon sink every year in the study period (Figure 15). This sink was strongest from 1955 to the late 1970s, driven by higher annual growth in PIU compared to the decades since. Carbon in SWDS grew every year, maintaining the harvested wood products carbon sink, while PIU stocks shrunk in some years, primarily in the 1980s and 2000s. The annual net change peaked at 0.227 TgC yr^{-1} in 1969 and was lowest in 2004 (0.011 TgC yr^{-1}).

The ten-year average flux (coincident with the forest ecosystem flux measurement period of 2002 to 2009 and 2012 to 2019) for the PIU C pool equated to 0.0005 TgC yr^{-1} and the SWDS average was 0.0335 TgC yr^{-1}. The positive numbers indicate that both pools, on average, grew over this period. The net average flux over this period equated to 0.034 TgC yr^{-1}.

The harvested wood products carbon flux can also be assessed as the difference between additions (harvest) and emissions (IPCC simple decay approach; Figure 16). The net values (green lines) in Figure 15 and Figure 16 are identical, but Figure 16 shows how annual harvest and emissions compare. Harvest has outpaced emissions with and without energy capture for the entire study period, though harvest only slightly outpaced emissions in the 1980s and 2000s (Figure 16).

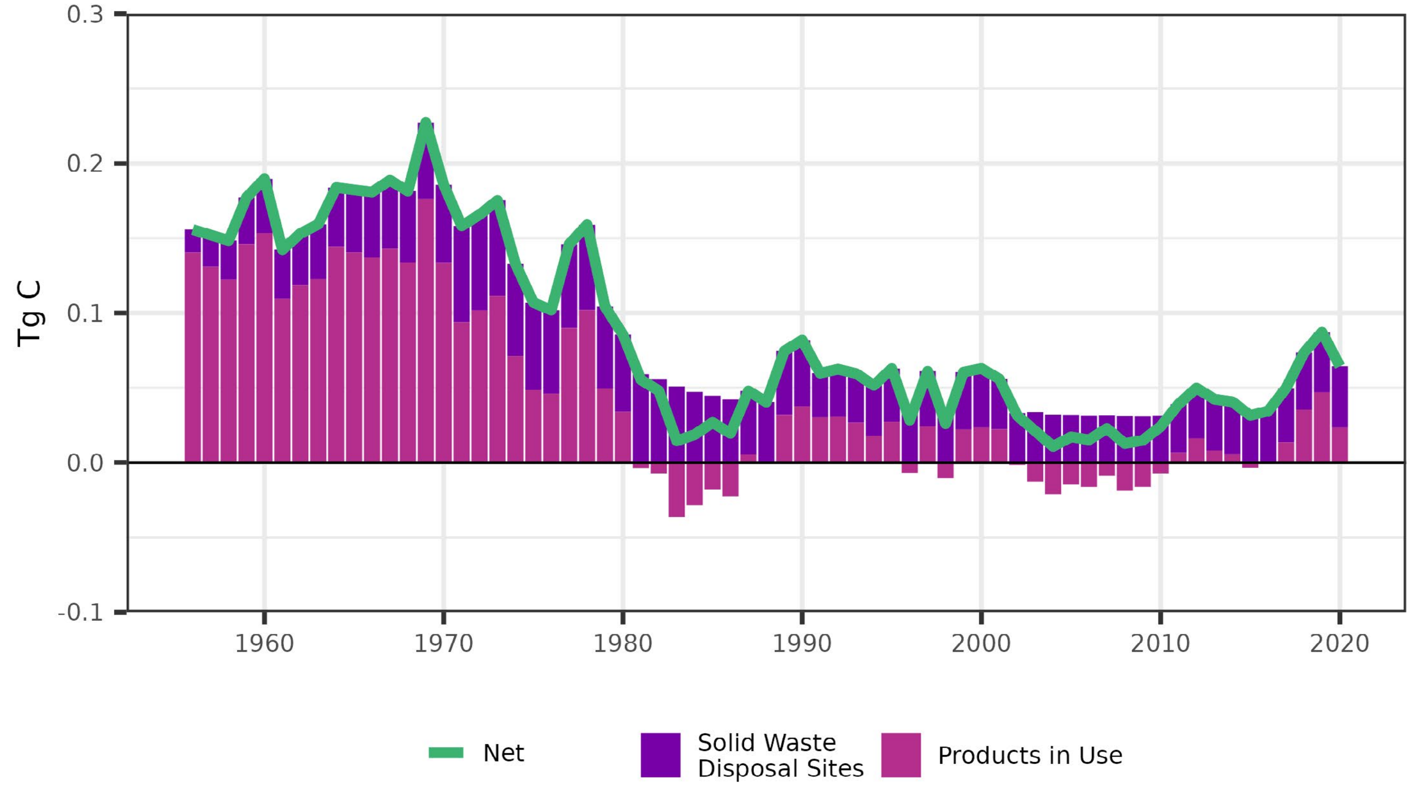


Figure 15. *Annual change in harvested wood product carbon pools (purples) and the annual net change for both pools (green line) using the IPCC production approach. Positive values represent annual growth of that carbon pool, while negative values indicate annual losses exceeded gains in that pool.*

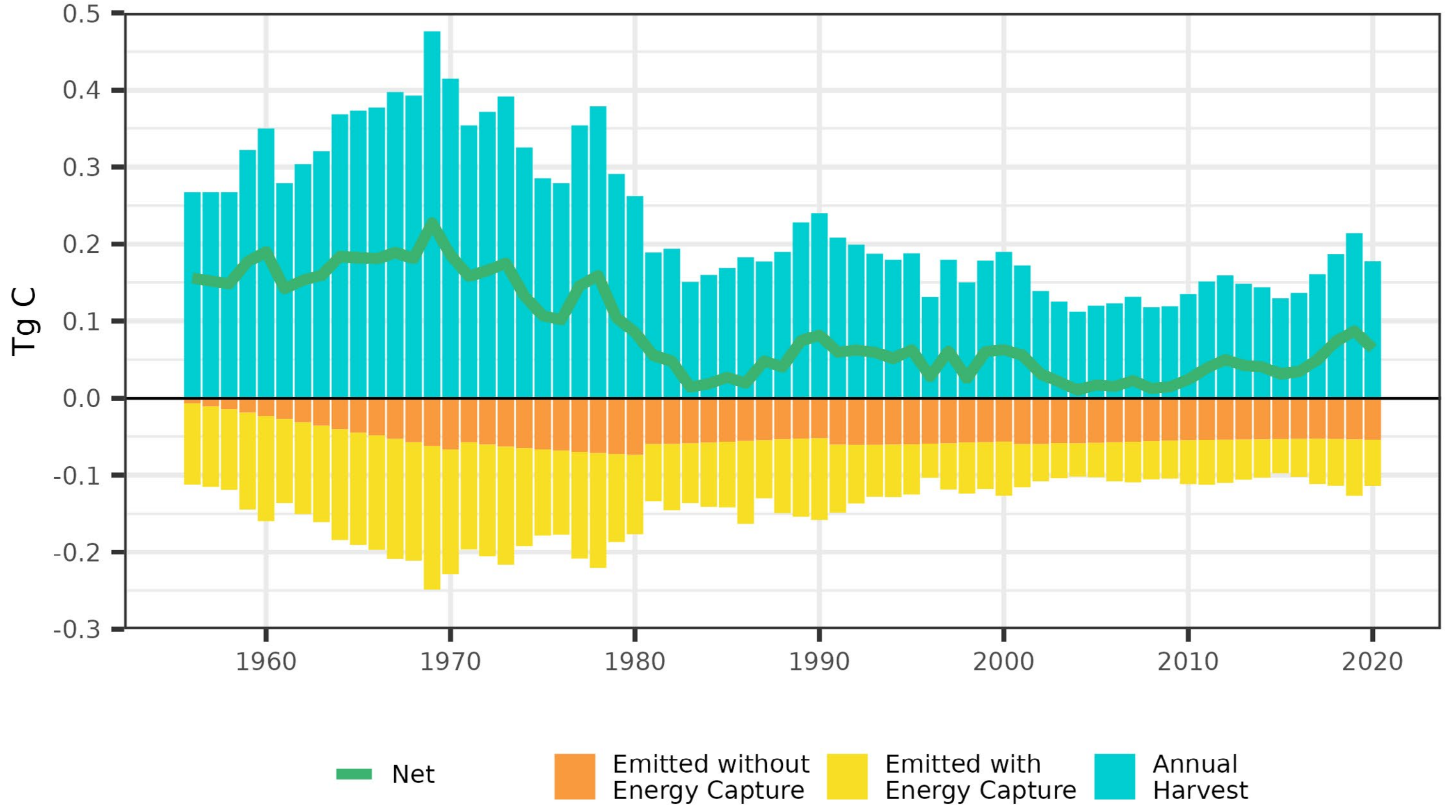


Figure 16. *Annual additions (harvest) and emissions from the harvested wood product carbon stocks and the annual net change (green line) using the IPCC simple decay approach.*

6 FOREST SECTOR CARBON: ECOSYSTEM AND HARVESTED WOOD PRODUCTS

We combined stocks and fluxes from the forest ecosystem and the harvested wood products to estimate the total forest sector carbon stocks and fluxes (Table 13 and Table 14). The Colorado forest sector stock for the 2010 to 2019 sampling period was 1,558.138 TgC. The forest ecosystem holds 99.6% of this carbon, far outsizing the harvested wood product stocks (0.4%).

The Colorado forest sector is a weak source of carbon, emitting 3.163 $TgCO2e\ yr^{-1}$ for the period tracking change between 2002 to 2009 and 2012 to 2019 (Table 14). The harvested wood products carbon sink was 4% of the magnitude of the forest ecosystem flux and methane and nitrous oxide fire emissions was 3%. This forest ecosystem flux represents forest remaining forest and these forest sector estimates do not include forest land use change. We cannot yet use FIA data in Colorado for reliable forest land use change estimates, but we estimate that areas changing to and from forest would be less than 5% of the forest remaining forest area and thus would have minimal impact on the forest sector net flux.

Table 13. *Stocks for the forest ecosystem, harvested wood products and total forest sector. More detailed reporting of the forest ecosystem and harvested wood products numbers are reported in Sections 4 and 5, respectively.*

	Stocks	
Carbon pool	**Total**	**SE**
	TgC	
Forest ecosystem	1,552.597	12.006
Harvested wood products	5.541	-
Total forest sector	1,558.138	-

Table 14. *Average annual flux for the forest ecosystem, methane (CH4) and nitrous oxide (N2O) fire emissions, harvested wood products and total forest sector.*

	Flux	
Carbon pool	**Total**	**SE**
	$TgC0_2e\ yr^{-1}$	
Forest ecosystem*	-3.183	-
Harvested wood products	0.125	-
CH_4 and N_2O fire emissions	-0.105	0.014
Total forest sector	-3.163	-

** Forest ecosystem flux includes down woody material and does not have a standard error (SE)*

7 DISCUSSION

7.1 Forest Ecosystem Carbon

Colorado's forests have been estimated to be the greatest emitter of forest carbon in the Rocky Mountain West (Domke et al., 2023; Walters et al., 2023). This first implementation of Colorado's forest carbon inventory found Colorado's forests hold more carbon and are losing less carbon than previous estimates (Table 15). Colorado is the first state outside of the Pacific coast states to estimate forest carbon stocks using this inventory approach adapted from California (Christensen et al., 2019a), Oregon (Christensen et al., 2019b) and Washington (Christensen et al., 2020), providing a more detailed and precise assessment of the state's carbon stock and fluxes. Each FIA region has unique data attributes and data collection histories that impact the implementation of this framework, such as the methods used to measure down woody material and how these have changed over the years. As the first state in the USFS's Rocky Mountain Research Station FIA region to implement this forest carbon accounting framework, we hope this effort can aid other states in the region interested in forest carbon inventories. We also worked to make this framework more accessible by adapting the forest ecosystem model to R statistical software, a free and open-source software.

This inventory enables multiple levels of data disaggregation to investigate forest carbon trends across the state. We summarized forest carbon stocks and fluxes across different geographic boundaries from the whole state down to the county. In addition to geographic boundaries, we also summarized by forest types, pools and disturbance classifications. For instance, this can enable comparing land ownership such as National Forests across the state identifying forests that have relatively large stocks and low carbon loss (Pike and San Isabel National Forest) to those that also have moderate stocks but high carbon loss (Rio Grande National Forest). However, as the resolution of the disaggregation becomes finer, the quantity of data (i.e., number of FIA plots) supporting the analysis may become too limited for reliable interpretation. For example, this can occur when looking at county level information on disturbance classifications or land ownership, especially for counties that are smaller or have limited forested area, but investigating stocks or net flux by county would have enough data to support reliable interpretations. In addition, when interpreting

results, it is important to recognize the relationships and correlations between groupings. For instance, when looking at carbon pool flux by land ownership, the Other federal ownership has a significantly lower loss of carbon than the U.S. Forest Service but this can largely be attributed to the large area of the pinyon/juniper forest type group that exists on Bureau of Land Management property in Colorado which has a lower net carbon loss than the forest type groups that dominate NFS lands. Further, due to its spatial scale, this inventory is not designed to inform stand-scale or project-level forest management. However, the results can inform statewide and landscape-level planning and prioritization.

This inventory highlights the impact that recent forest disturbances have had on Colorado's forest carbon stocks and fluxes. In undisturbed forests, forests sequestered more carbon than they released, providing a net sink for the state. However, forests impacted by disturbance were a source of carbon. It is important to note that carbon flux is highly sensitive to the time period assessed; results would certainly differ if we were to analyze fluxes across a longer time, such as 1900 to 2019. Yet, the growth of Colorado forests is not keeping pace with the recent mortality they are experiencing which can be seen in the aboveground live tree pool growth, mortality and removals (Table 2). Insect and disease outbreaks had the greatest impact of all disturbances, affecting nearly a third of the state's forests and accounting for nearly two thirds of the carbon loss from disturbances. The imprint of widespread mountain pine beetle and spruce beetle outbreaks that have impacted Colorado's forests in recent decades (Colorado State Forest Service, 2022) are evident in the state's carbon fluxes. Lodgepole pine forests in the northwest CSFS area and Engelmann spruce in the southwest and northwest CSFS areas were especially severely impacted by these bark beetle outbreaks and the associated forest type groups in these regions had large losses in forest ecosystem carbon.

Colorado forest types range from these dense lodgepole pine stands to large, open ponderosa pine forests. ***Photo: Field Peterson, CSFS***

The aboveground dead, belowground dead and down woody material carbon pools increased with the high tree mortality rates. While these pools are currently storing carbon lost from the live tree pools, these stocks will decompose slowly over time, releasing carbon back to the atmosphere. The resilience of Colorado's forest carbon sinks will largely be related to the ability of these forests to recover after disturbance. In some cases, these forests are recovering, such as lodgepole pine forests after mountain pine beetle outbreaks, where recovery is generally observed but with an altered species composition (e.g. Rhoades et al., 2020). Conversely, post-wildfire tree regeneration is hindered in many cases, particularly in large high burn severity patches, due to a litany of factors exacerbated by warm, dry conditions (e.g. Chambers et al., 2016; Coop et al., 2020; Davis et al., 2019; Rodman et al., 2020; Woolman et al., 2022). Further, large scale disturbances have continued since the end of this 2019 reporting period. Colorado's severe 2020 wildfire season will be captured in the state's carbon inventory as more burned plots are measured by FIA in the coming years, likely making the state's forests a larger carbon source.

The fir/spruce/mountain hemlock forest type group held the largest carbon stock for Colorado with the highest carbon density per area, but this forest type group had the second largest net loss of carbon. Insects and diseases have impacted this forest type group, especially in the CSFS southwest area, for multiple decades. Similarly, the aspen/birch forest type group had the third largest forest carbon stock and covered the third most area but experienced significant mortality in the past two decades from a combination of prolonged drought, herbivory, insects and diseases (Binkley & Romme, 2020; Dudley et al., 2015; Worrall et al., 2015). The aspen/birch forest type group was the forest type with the largest loss of carbon in the CSFS northwest area. Although the pinyon/juniper forest type group had low carbon density, it held the second largest forest carbon stock in Colorado due to the large area it covered. The pinyon/juniper forest type group experienced large die-off in the early 2000s related to drought and associated Ips beetle outbreaks (Allen et al., 2010; Breshears et al., 2009; Redmond & Barger, 2013). The years analyzed in this inventory captured the recovery from these forest disturbances, marked by regeneration where new trees were able to establish in areas previously impacted by insects, disease, wildfire and prolonged drought. This underscores the importance of considering the context of the years selected for analysis and how they may relate to previous or ongoing disturbance events.

Three previously published forest carbon inventories had values for Colorado that can be compared to the estimates provided in this report. Broadly, our results show Colorado having higher stocks and lower carbon loss than previous estimates and we provide error estimates that are often not included or are large. When error estimates were provided (e.g., National GHG Inventory; U.S. EPA, 2023b; Walters et al., 2023), the range of values was large and indicated that Colorado could be a source or a sink of carbon emissions and encompasses the flux values found in this report.

When comparing carbon pools from the existing report that provides this level of detail, we report smaller net carbon gains (less positive) in the down woody material (60% less) and soil (84% less) pools but smaller loss of carbon (less negative) from aboveground (74% greater) and belowground (60% greater) live and dead tree pools (U.S. EPA, 2023b; Walters et al., 2023). Further, we estimate larger stocks in aboveground live and dead tree biomass (46% greater), belowground biomass (31% greater), litter (10% greater) and soil (22% greater) pools and lower stocks in the down woody material pool (45% less) (U.S. EPA, 2023b; Walters et al., 2023). The existing forest carbon inventories all had unique attributes that prohibit direct comparisons to the values provided in this report (Appendix A). However, broad comparisons can cautiously be made and Table 15 presents the values from these reports that most closely align with our reporting. Some of the more important considerations when comparing inventories is the method used to calculate flux (stock difference versus difference between remeasured plots), the pools included and the forest land change categories included (Table 15). These all significantly impact stock and flux calculations. For example, Hoover and Smith (2021) limited their estimate to aboveground live trees omitting pools that currently are estimated in this report to be expanding (standing dead and down woody material) while the National GHG Inventory used annual changes in FIA stocks to estimate fluxes versus the difference between the same remeasured plots used here. Additionally, our inventory incorporated new allometric biomass equations and carbon fractions from the NSVB update to estimate carbon stored in each tree measured (Westfall et al., 2023). These carbon estimation methods are an improvement on equations used previously in the other inventories and likely are a reason for our higher stock estimates as the NSVB update resulted in higher biomass estimates in the Rocky Mountain region.

Table 15. *Similarities and differences among the methods and results of other statewide forest carbon inventory publications with a similar reporting year to this report.*

REPORT NAME	DATA SOURCE(S)[2]	REPORTING YEAR	CARBON POOLS INCLUDED	FOREST LAND CHANGE CATEGORY	STOCK (TGC)	FLUX (TGC YR-1)[6]
This report	FIA accessed Dec 8, 2023	Flux 2002 to 2009 and 2012 to 2019, Stocks 2010 to 2019	Aboveground live and dead biomass, belowground live and dead biomass, down woody material, litter, soil	Forest land remaining forest land	1,552.597 ± 23.532 (4)	-0.867 (7)
National GHG Inventory Dataset (1)	NRI, FIA and the NLCD	2019	Aboveground biomass, belowground biomass, dead wood, litter, soil organic carbon	Forest land remaining forest land	1,264.91	-3.21
				Forest land converted to nonforest	Not provided	-0.46
				Nonforest converted to forest land	Not provided	0.26
CO GHG Inventory (1)	Default EPA SIT values except for wildfire acres burned (NIFC)	2018	Aboveground biomass, belowground biomass, dead wood, litter, mineral soil	Not stated	Not provided	-2.91
Hoover and Smith 2021 (1)	2020 NGHGI and FIA accessed June 2020	Before June 2020, possibly 2017 (3)	Aboveground live tree	Forest land remaining forest land	276.56 (5)	-4.13 (5)

1) Other statewide forest carbon inventory publications include "Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990 to 2019: Estimates and quantitative uncertainty for individual states" (National GHG Inventory Dataset; Walters et al., 2021), "Colorado 2021 Greenhouse Gas Inventory Update" (Colorado GHG Inventory; Taylor, 2021), and "Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States" (Hoover and Smith 2021). These publications use the FIA definition for tree area and cover requirements. If an area is surrounded by urban or developed lands, it is classified as settlements rather than forest land in the National GHG Inventory and 2021 Colorado GHG Inventory.

2) Data sources include the *National Resources Inventory* (NRI), *National Land Cover Dataset* (NLCD), and *Forest Inventory and Analysis* (FIA).

3) Hoover and Smith 2021 did not state the reporting year. It did state that the FIA database was accessed in June 2020. The NGHGI released in the same year reported FIA data in Colorado was available up to 2017.

4) The range (i.e., ±) represents a 95% confidence interval.

5) Hoover and Smith 2021 provided estimates broken up by forest type (hardwoods, softwoods, and woodlands) and these were added together to provide one estimate in the table.

6) Each publication designated negative values to indicate a net carbon uptake; we switched this to negative values indicate an emission to be consistent with this report's results.

7) Flux of the down woody material pool is calculated from a subset of plots.

7.2 Harvested Wood Products Carbon

The 2021 Colorado GHG Inventory (COGHGI) was the only existing source providing a statewide harvested wood product inventory for Colorado. It identified the harvested wood products sector as a net carbon sink of 0.152 TgC yr^{-1} in 2018, which is 78% higher than our report's average annual net harvested wood product estimate of 0.034 TgC yr^{-1} (Taylor, 2021). Differences in methodology and data sources between COGHGI and our report make direct comparisons challenging. For example, COGHGI utilized the EPA's State Inventory Tool (SIT) LULUCF module and its' default values to estimate total carbon fluxes for wood products and landfills for the years 2005 to 2018. The report did not disaggregate carbon change by individual pools (e.g., products in use or SWDS) or include any associated error estimates. The 2023 update of the COGHGI transitioned from using the EPA SIT to employing data from the national inventory by state, as detailed in Appendix A. This approach does not disaggregate harvested wood products to the state level, so it was not incorporated in the 2023 edition of the COGHGI.

We utilized the best available and longest-running harvest data we could find from 1954 to 2019 in this report. We found NFS lands to be the primary timber producers in Colorado until the mid-1990s (Figure 13). While some bias may exist due to the data sources and potential lack of data for other land ownerships, the timber product output dynamics observed seem to mirror shifts in the state's economy and land management practices. During the late 1970s and early 1980s, timber markets in the western US experienced significant changes driven by log supply shortages and evolving market conditions. Declining timber product output at the end of the 1970's reflected economic uncertainty in the United States. Economic scarcity and decreased home building likely account for the observed decrease in timber prices during this period (Skog & Risbrudt, 1982). Notably, in the late 1970s and early 1980s, Colorado witnessed the closure of several large sawmills, including those in Durango, Pagosa Springs and Walden. These closures were a result of the combined impact of log supply shortages and market conditions. By the late 1990s, there was an increase in timber product output on non-NFS lands, as mills endeavored to remain operational. Concurrently, this period saw a rise in large wildfires and outbreaks of insects and diseases, which further prompted timber activities on non-federal lands.

Annually, a portion of the SWDS pool is replenished in proportion to the additions made in the PIU pool, even if the PIU pool decreases in an individual year. This is because the model accounts for manufacturing and construction waste by transferring 8% of the carbon in primary products directly to the discarded pool each year. Wood products with a shorter lifespan, such as crates, pallets and fencing materials, enter the waste stream relatively quickly after production, contributing to the SWDS stocks. These stocks are relatively constant over time, as they include the accumulation of stocks from the previous year, the addition of new discarded materials and the subtraction of decomposed materials. This, combined with the regular retirement of longer lasting products, sustains the SWDS carbon stock. As the timber product output decreased in the 1970s, there was a noticeable shift in the annual end-use allocation of timber products. Between 1954 and 1980, the distribution was 39% for immediate fuel use, 14% for short-term products (1-6 years), 27% for medium-term products (7-30 years) and 20% for long-term products (31 or more years; Appendix Figure 1). However, from 1981 to 2019 this trend shifted: short-term products decreased by 23%, medium-term products increased by 41% and long-term products decreased by 41%.

Colorado's harvested wood products served as a carbon sink every year in the study period, largely driven by carbon stored in SWDS (Figure 15). This sink was influenced by a reduction in PIU from 1981 to 1986 and again in 1996 to 2010, in which fewer products entered the PIU pool. Ongoing declines in the production and end-use allocation of new timber products could reduce the strength of this carbon sink. Albeit a relatively minor component of the state's total forest carbon, these findings underscore the importance of silviculture treatments and the harvested wood products industry in sustaining this carbon sink. Maximizing woody biomass use generates value that can aid in offsetting the growing expenses associated with forest management treatments, while continuing to act as a long-term carbon sink throughout a product's lifecycle.

In comparison to west-coast states like Washington, Oregon and California, which benefit from different climates, forest types and larger industry infrastructure, Colorado's timber production is notably smaller and more focused on local and regional markets. Understanding this distinction is crucial to recognizing the state's timber production potential and limitations. Key factors such as forest type, disturbances, ownership, market conditions and production, play significant roles in determining the feasibility and sustainability of timber harvesting, particularly at local and regional levels. However, within these variances lie unique opportunities. The regional differences in feedstock types and available infrastructure mean that what might be an excess in one region could be a valuable resource in another (CSFS Biomass Assessment, in review). These discrepancies offer room for innovative applications and the development of new markets, tailored to the specific characteristics of each supply chain. By recognizing and adapting to these regional nuances, it's possible to maximize the utility and economic potential of these resources at both local and broader scales.

Forest management, along with the allocation and use of harvested wood products, plays a crucial role in shaping the future dynamics of carbon stored in those products across the state. These results have several applications for land managers, policymakers and the public, as they provide a foundation for crafting strategies in natural resource management, climate mitigation and adaptation related to carbon storage in harvested wood products. The 2020 Colorado Forest Action Plan Resource Strategy section outlined the following priority strategies for forest products industry improvement: (1) fairly and equitably support increased forest industry capacity to sustainably address forest health issues and offset the cost of treatments, (2) develop low-interest loans for the forest products industry, (3) launch grants to incentivize use of low-value wood, (4) promote state tax incentives, including extension of exemption for blue stain wood products (beetle-kill) and (5) stimulate infrastructure and markets for handling small diameter material (Colorado State Forest Service, 2020). This report continues to provide information to support these strategies.

7.3 Strategies to Improve the Inventory

Improvements to Forest Ecosystem Model

Colorado FIA plots are re-measured every ten years. This report is based on FIA data through 2019, which includes a second measurement on 80% of Colorado's FIA plots. We thus use 80% of the state's plots to calculate fluxes. As FIA releases the remaining 20% of remeasurement data to complete two full panels in Colorado and these updates are incorporated into future inventories, the precision of estimates of change will improve.

Changes over time to the FIA protocol on down woody material measurements in the FIA Rocky Mountain region led us to calculate down woody material changes only on phase 3 plots, representing a sixteenth of the plots used for stock estimates and fluxes of other carbon pools. Estimates of change in down woody material will improve as more plots are re-measured using consistent methods. There will be enough phase 2 plots measured with the current down woody material methods to better calculate change by later in the 2020s and into the 2030s, with accuracy and precision improving with each year of data collected. Two full panels of consistent down woody material measurements will be completed in 2033. The FIA program continues to evaluate their methods' accuracy, particularly with respect to down woody material. The FIA protocol effectively tracks the transition of live trees to standing dead trees. However, once a tree falls, it is difficult to continue tracking the condition and fate of that tree. Fallen trees can be captured in the down woody material transect surveys, but with less information about the tree and potentially with lower accuracy.

Changes to forest conditions take time to be reflected in this carbon accounting framework. The impact of disturbances is captured over the ten-year period it takes to re-measure each plot. Three of the state's largest fires on record burned 550,000+ acres in 2020 (Colorado State Forest Service, 2022). These fires will begin being represented as post-fire plots are measured but won't be fully captured in plot changes until 2030 measurements are conducted. Insects and diseases, such as spruce beetles and western spruce budworm, continued to impact thousands of acres across multiple forest types. These disturbances will have large impacts on future inventories of forest carbon in Colorado.

The FIA program identifies non-forest land-uses either by inventory crews (on the ground) or using recent imagery (for non-field visited plots), making it possible to classify non-forest lands into other land-use categories (i.e., grassland, cropland, wetland). However, we do not account for forest change in this inventory, as the recorded changes are currently unreliable due to definition and procedural changes and observation errors. This inventory framework could incorporate forest change in the future if these changes in forest status were verified. This verification has been done in some FIA regions such as the Pacific Northwest and is being considered in other regions.

While we did estimate methane and nitrous oxide fire emissions, future reports could improve accounting of fire emissions. Improvements to parameters such as the emission factors and accounting for other greenhouse gases from fire besides methane and nitrous oxide would help to better estimate carbon and other greenhouse gas emissions from fires. We used IPCC emission factors which are coarse (i.e., a single value for temperate forests) and could be updated to be more representative of Colorado's forests. Research is ongoing to understand how well FIA protocols capture changes in carbon from fire in this region.

We present sampling error in this report, but there are other sources of uncertainty in these carbon estimates that this framework does not quantify. For example, we do not propagate uncertainty from measurement error or errors in the allometric biomass equations, which can be substantial (Vorster et al., 2020). Additionally, some of the carbon pools we tracked (soil, aboveground understory and belowground understory) are modeled values with prediction errors of their own.

Improvements to Harvested Wood Products Model

While carbon in harvested wood products constitutes a small fraction of Colorado's forest carbon, there are improvements that could be made to the harvest wood products model. The accuracy of the model output is contingent upon the quality of input data. The data sources used in this report indicate that annual harvests were mostly dominated by NFS lands, with notable data gaps among Native American and Bureau of Land Management forested lands. Additionally, we lack data from before 1954, even though products manufactured before this year may still be in use or storing carbon. The timber product ratios we derived from USFS Cut and Sold Reports provided a finer detail compared to other data sources, however one limitation is their focus on NFS lands. Further, our analysis

employs regional defaults for various parameters, such as the proportion of materials recycled or burned without energy capture. These defaults provide a coarse representation of these pools but may not precisely capture the specific conditions in Colorado. Ongoing efforts to refine some of these parameters (e.g., recycling rates) to better reflect state-specific conditions can be implemented in future implementations of this inventory. Future iterations of this report could also be enhanced by integrating other data sources, including records from the Colorado Forest Tracker, an interagency resource of completed forest management locations across Colorado (Mueller et al., 2023). In addition, developing Colorado-specific primary product ratios that reflect the unique characteristics and temporal variations of the state's timber products is an opportunity for enhancement.

8 CONCLUSION

This report fulfills the requirement in HB 22-1012 for the Colorado State Forest Service to develop a publicly accessible carbon accounting framework for Colorado. It presents the first implementation of this framework through reporting year 2019, based on FIA plots measured between 2002 and 2019 and harvested wood products data from 1954 to 2019. Colorado's forest sector held 1,558.138 TgC and emitted an average of 3.163 $TgCO_2e\ yr^{-1}$, with the vast majority of this storage and flux coming from the forest ecosystem. As we disaggregated findings by ownership, forest type, county, etc., one overarching theme to our findings is that carbon trends are nuanced across Colorado and reflect a myriad of factors shaping the state's forests: current and historical management practices, disturbances and climate change. Some counties and forest types are continuing to sequester more than they are emitting, while others are serving as sources of carbon.

The goal of this project was to build a forest carbon accounting framework for Colorado and to provide a current forest carbon inventory. This thorough characterization of the statewide and regional forest carbon stocks and fluxes provides a foundation to inform a range of efforts from statewide policy making to regional forest management planning and local climate change adaptation and mitigation initiatives. Following this report, HB22-1012 includes the development of a forest carbon co-benefit framework which will connect this inventory with the 2020 Colorado Forest Action Plan's goals, strategies and approaches. It will identify on-the ground project-level practices that serve to improve carbon sequestration and storage within Colorado's forested systems. This forest carbon accounting framework is built on data that is continuously collected and updated to reflect our ever-changing forests and harvested wood products industry. The inventory will be updated as new data becomes available and as methodological refinements are made to the carbon accounting framework.

The West Bench of the Grand Mesa offers scenic stands of fall color. ***Photo: Kamie Long, CSFS***

REFERENCES

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences,* 113(42), 11770–11775. *https://doi.org/10.1073/pnas.1607171113*

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J. H., Allard, G., Running, S. W., Semerci, A., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management,* 259(4), 660–684. *https://doi.org/10.1016/j.foreco.2009.09.001*

Bechtold, W. A., & Patterson, P. L. (2015). The enhanced forest inventory and analysis program - national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p. *https://www.fs.usda.gov/treesearch/pubs/20371*

Binkley, D., & Romme, B. (2020). Conversations from Southern Colorado and Northern New Mexico. *https://digitalcommons.usu.edu/aspen_bib/7856*

Bolinger, B., Lukas, J., Schumacher, R., & Goble, P. (2024). Climate Change in Colorado, 3rd edition. Colorado State University. *https://doi.org/10.25675/10217/237323*

Breshears, D. D., Myers, O. B., Meyer, C. W., Barnes, F. J., Zou, C. B., Allen, C. D., McDowell, N. G., & Pockman, W. T. (2009). Tree die-off in response to global change-type drought: Mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment,* 7(4), 185–189. *https://doi.org/10.1890/080016*

Bureau of Land Management. (2023). Timber Transaction Data. Available upon request from the Bureau of Land Management.

Burrill, E. A., DiTommaso, A. M., Turner, J. A., Pugh, S. A., Christiansen, G., Perry, C. J., Conking, B. L., Lepine, L., Walker, D., & Williams, M. A. (2023). The Forest Inventory and Analysis Database: Database Description and User Guide for Phase 2 (version 9.1). U.S. Department of Agriculture, Forest Service. *https://www.fia.fs.usda.gov/library/database-documentation/index.php*

Chambers, M. E., Fornwalt, P. J., Malone, S. L., & Battaglia, M. A. (2016). Patterns of conifer regeneration following high severity wildfire in ponderosa pine – dominated forests of the Colorado Front Range. *Forest Ecology and Management,* 378, 57–67. *https://doi.org/10.1016/j.foreco.2016.07.001*

Christensen, G. A., Gray, A. N., Kuegler, O., Tase, N. A., Rosenberg, M., Loeffler, D., Anderson, N., Stockmann, K., & Morgan, T. A. (2019a). AB 1504 California Forest Ecosystem and Harvested Wood Product Carbon Inventory: 2017 Reporting Period. U.S. Forest Service agreement no. 18-CO-11052021-214, 17-CO-11261979-086, California Department of Forestry and Fire Protection agreement no. 8CA04056 and 8CA03714 and the University of Montana. California Department of Forestry and Fire Protection and California Board of Forestry and Fire Protection. *https://bof.fire.ca.gov/media/8026/4-final_1504_forest_ecosys_hwp_c_2017_13feb19_full.pdf*

Christensen, G. A., Gray, A. N., Kuegler, O., & Yost, A. C. (2019b). Oregon Forest Ecosystem Carbon Inventory: 2001-2016 (Agreement between the U.S. Forest Service, Pacific Northwest Research Station, and the Oregon Department of Forestry (PNW Agreement No. 18-C-CO-11261979-019), p. 347). Oregon Department of Forestry. *https://www.oregon.gov/odf/board/bof/20201104-oregon-forest-ecosystem-carbon-inventory-2001-2016.pdf*

Christensen, G. A., Gray, A. N., Kuegler, O., & Siemann, D. (2020). Washington Forest Ecosystem Carbon Inventory: 2002-2016 (Agreement between the U.S. Forest Service, Pacific Northwest Research Station, and Washington Department of Natural Resources (PNW Agreement No. 18-C-CO-11261979-066), p. 234). Washington State Department of Natural Resources. *https://www.dnr.wa.gov/publications/em_wa_carbon_inventory_final_111220.pdf*

Colorado Department of Natural Resources. (2023). Colorado's Strategic Plan for Climate-Smart Natural and Working Lands. *https://ag.colorado.gov/conservation/agricultural-drought-and-climate-resilience-office-adcro/strategic-plan-for-climate*

Colorado Energy Office. (2021). Colorado Greenhouse Gas Pollution Reduction Roadmap. Colorado Energy Office. *https://energyoffice.colorado.gov/climate-energy/ghg-pollution-reduction-roadmap*

Colorado Energy Office. (2024). Colorado Greenhouse Gas Pollution Reduction Roadmap 2.0. Colorado Energy Office. *https://energyoffice.colorado.gov/climate-energy/ghg-pollution-reduction-roadmap-20*

Colorado Natural Heritage Program. (2021). The Colorado Ownership, Management and Protection Map (COMaP).

Colorado Parks and Wildlife. (2019). Colorado Parks and Wildlife State Forest State Park 2019 Management Plan. *https://cpw.state.co.us/placestogo/parks/StateForest/Documents/Final-Management-Plan.pdf*

Colorado State Forest Service. (2020). Colorado Forest Action Plan. *https://csfs.colostate.edu/media/sites/22/2020/10/2020-ForestActionPlan.pdf*

Colorado State Forest Service. (2022). 2022 Report on the Health of Colorado's Forests. *https://csfs.colostate.edu/forest-management/forest-health-report/*

Colorado State Forest Service. (2023). Colorado Wildfire Risk Assessment (CO-WRA). *https://coloradoforestatlas.org/customers/colorado/manuals/CO-WRA_2022_Final_Report_20230724.pdf*

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Z. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M. Parisien, S. Prichard, and K. C. Rodman. 2020. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *BioScience* 70(8):659–73. doi: 10.1093/biosci/biaa061. https://doi.org/10.1093/biosci/biaa061

Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., Parks, S. A., Sala, A., & Maneta, M. P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences,* 116(13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

Domke, G. M., Perry, C. H., Walters, B. F., Nave, L. E., Woodall, C. W., & Swanston, C. W. (2017). Toward inventory-based estimates of soil organic carbon in forests of the United States. *Ecological Applications,* 27(4), 1223–1235. https://doi.org/10.1002/eap.1516

Domke, G. M., Walters, B. F., Giebink, C. L., Greenfield, E. J., Smith, J. E., Nichols, M. C., Knott, J. A., Ogle, S. M., Coulston, J. W., & Steller, J. (2023). Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990-2021. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/research/treesearch/66035

Dudley, M. M., Burns, K. S., & Jacobi, W. R. (2015). Aspen mortality in the Colorado and southern Wyoming Rocky Mountains: Extent, severity, and causal factors. *Forest Ecology and Management,* 353, 240–259. https://doi.org/10.1016/j.foreco.2015.06.002

Forest Inventory and Analysis. (2023). Forest Inventory and Analysis Glossary - Standard Terminology. https://www.fs.usda.gov/research/understory/forest-inventory-and-analysis-glossary-standard-terminology

Groom, J., & Tase, N. A. (2022). Harvested Wood Products Carbon Model, Version R Documentation. https://jeremygroom.github.io/HWP-vR-Documentation/

Hayes, S. W., Bingaman, C. A., Morgan, T. A., Simmons, E. A., Marcille, K. C., & Shaw, J. D. (2021). The Four Corners Timber Harvest and Forest Products Industry, 2016. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://www.fs.usda.gov/research/treesearch/62457

Hayes, S. W., Morgan, T. A., Berg, E. C., Daniels, J. M., & Thompson, M. (2012). The Four Corners Timber Harvest and Forest Products Industry, 2007. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://www.fs.usda.gov/research/treesearch/40885

Heald, S. (2019). Colorado 2015 greenhouse gas inventory update including projections to 2020 & 2030 (p. 147). Colorado Department of Public Health & Environment, Air Pollution Control Division.

Higuera, P. E., Shuman, B. N., & Wolf, K. D. (2021). Rocky Mountain subalpine forests now burning more than any time in recent millennia. *Proceedings of the National Academy of Sciences,* 118(25), e2103135118. https://doi.org/10.1073/pnas.2103135118

Hoover, C. M., & Smith, J. E. (2021). Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States. *Carbon Balance and Management,* 16(1). https://doi.org/10.1186/s13021-021-00179-2

Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe, eds. Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M. Tignor, H.L. Miller, Z. Chen, eds. New York: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2014). 2013 Revised supplementary methods and good practice guidance arising from the Kyoto Protocol. T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda and T.G. Troxler, eds. Switzerland: Intergovernmental Panel on Climate Change.

Irey, B. (2023). Colorado's Forest Products Industry and Timber Harvest, 2020 [Unpublished data]. University of Montana, Bureau of Business and Economic Research.

McKeever, D. B. (2009). Estimated annual timber products consumption in major end uses in the United States, 1950-2006. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. https://www.fs.usda.gov/treesearch/pubs/33882

McKeever, D. B., & Howard, J. L. (2011). Solid wood timber products consumption in major end uses in the United States, 1950-2009: a technical document supporting the Forest Service 2010 RPA assessment. https://doi.org/10.2737/FPL-GTR-199

Morgan, T. A., Dillon, T., III.Keegan, C. E., Chase, A. L., & Thompson, M. T. (2006). The Four Corners Timber Harvest and Forest Products Industry, 2002. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://www.fs.usda.gov/research/treesearch/22861

Morgan, T. A., Donahue, T. S., Dillon, T., Yost, A., & Groom, J. (2022). Oregon Harvested Wood Products Carbon Inventory 1906 – 2018 (Report Completed through Agreement No. 18-CO-11261979-074 between the U.S. Forest Service, Pacific Northwest Research Station, and the Oregon Department of Forestry; and Agreement No. 18-CR-11261979-095 between the U.S. Forest Service, Pacific Northwest Research Station, and the University of Montana, Bureau of Business and Economic Research.). Oregon Department of Forestry. *https://www.oregon.gov/odf/Documents/forestbenefits/oregon-harvested-wood-products-carbon-inventory-report-1906-2018.pdf*

Mueller, S., Wolk, B., Kotlinski, N., Dannels, R., Green, A., & Fordham, A. W. (2023). Colorado Forest Management Activity Tracker (Forest Tracker). *https://csfs.colostate.edu/colorado-forest-tracker/*

Nichols, M. C., Morgan, T. A., Christensen, G. A., & Tase, N. A. (2020). Estimated Carbon Stored in Harvested Wood Products in Washington, USA: 1906 – 2018 (Report Completed through an Agreement between the U.S. Forest Service and the Washington Department of Natural Resources). Washington State Department of Natural Resources. *https://www.dnr.wa.gov/publications/em_wa_carbon_121420.pdf*

Redmond, M. D., & Barger, N. N. (2013). Tree regeneration following drought- and insect-induced mortality in piñon-juniper woodlands. *New Phytologist,* 200(2), 402–412. *https://doi.org/10.1111/nph.12366*

Rhoades, C. C., Hubbard, R. M., Elder, K., Fornwalt, P. J., Schnackenberg, E., Hood, P. R., & Tinker, D. B. (2020). Tree regeneration and soil responses to management alternatives in beetle-infested lodgepole pine forests. *Forest Ecology and Management,* 468, 118182. *https://doi.org/10.1016/j.foreco.2020.118182*

Rodman, K. C., Veblen, T. T., Battaglia, M. A., Chambers, M. E., Fornwalt, P. J., Holden, Z. A., Kolb, T. E., Ouzts, J. R., & Rother, M. T. (2020). A changing climate is snuffing out post-fire recovery in montane forests. *Global Ecology and Biogeography,* 29(11), 2039–2051. *https://doi.org/10.1111/geb.13174*

Skog, K. E. (2008). Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal,* 58(6), 56–72.

Skog, K., & Risbrudt, C. (1982). *Trends in Economic Scarcity of U.S. Timber Commodities* (FPL 11) [Resource Bulletin]. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States (Gen. Tech. Rep. NE-343; p. 216). U.S. Department of Agriculture, Forest Service, Northeastern Research Station. *https://doi.org/10.2737/NE-GTR-343*

Sorenson, C. B., Hayes, S. W., Morgan, T. A., Simmons, E., Scudder, M., McIver, C., & Thompson, M. T. (2016). The Four Corners Timber Harvest and Forest Products Industry, 2012 (Resource Bulletin RMRS-RB-21; p. 62). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. *https://www.fs.usda.gov/research/treesearch/50961*

Stockmann, K., Anderson, N., Young, J., Skog, K., Healey, S., Loeffler, D., Butler, E., Jones, J. G., & Morrison, J. (2014). Estimates of carbon stored in harvested wood products from United States Forest Service Rocky Mountain Region, 1906-2012.

Swanston, C. W., Janowiak, M. K., Brandt, L. A., Butler, P. R., Handler, S., Shannon, D., Lewis, A. D., Hall, K., Fahey, R. T., Scott, L., Kerber, A., Miesbauer, J. W., Darling, L., Parker, L., & Pierre, M. S. (2016). Forest Adaptation Resources: Climate change tools and approaches for land managers, 2nd ed (Gen. Tech. Rep. NRS-GTR-87-2, p. 161). U.S. Department of Agriculture, Forest Service, Northern Research Station. *https://doi.org/10.2737/NRS-GTR-87-2*

Taylor, T. (2021). Colorado 2021 Greenhouse Gas Inventory Update. Colorado Department of Public Health & Environment, Air Pollution Control Division. *https://cdphe.colorado.gov/environment/air-pollution/climate-change/GHG-inventory*

Twyman, M., Hill, S., Banta, K., & Billingsley, R. (2023). Colorado 2023 Statewide Inventory of Greenhouse Gas Emissions and Sinks With Historical Emissions from 2005 through 2020. *https://cdphe.colorado.gov/environment/air-pollution/climate-change/GHG-inventory*

U.S. Department of Agriculture, Forest Service. (2022). *Cut and Sold Report* [Tabular]. Forest Service Corporate Data Warehouse. *https://www.fs.usda.gov/forestmanagement/products/cut-sold/index.shtml*

U.S. Environmental Protection Agency (U.S. EPA). (2020a). *Annexes to the Inventory of U.S. GHG Emissions and Sinks: 1990-2018.* U.S. Environmental Protection Agency. *https://www.epa.gov/sites/default/files/2020-04/documents/us-ghg-inventory-2020-annexes.pdf*

U.S. Environmental Protection Agency (U.S. EPA). (2020b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* (EPA 430-R-20-002). U.S. Environmental Protection Agency. *https://www.epa.gov/sites/default/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf*

U.S. Environmental Protection Agency (U.S. EPA). (2023a). *Annexes to the Inventory of U.S. GHG Emissions and Sinks: 1990-2018.* U.S. Environmental Protection Agency. *https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Annexes.pdf*

U.S. Environmental Protection Agency (U.S. EPA). (2023b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021* (EPA 430-R-23-002). U.S. Environmental Protection Agency. *https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021*

Vorster, A. G., Evangelista, P. H., Stovall, A. E. L., & Ex, S. (2020). Variability and uncertainty in forest biomass estimates from the tree to landscape scale: the role of allometric equations. *Carbon Balance and Management,* 15(1), 8. *https://doi.org/10.1186/s13021-020-00143-6*

Walters, B. F., Domke, G. M., Nowak, D. J., Smith, J. E., & Ogle, S. M. (2021). Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2019: Estimates and quantitative uncertainty for individual states. Forest Service Research Data Archive. *https://doi.org/10.2737/RDS-2021-0035*

Walters, B. F., Domke, G. M., Greenfield, E. J., Smith, J. E., & Ogle, S. M. (2023). Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2021: Estimates and quantitative uncertainty for individual states, regional ownership groups, and National Forest System regions. Forest Service Research Data Archive. *https://doi.org/10.2737/RDS-2023-0020*

Wear, D. N., & Coulston, J. W. (2015). From sink to source: Regional variation in U.S. forest carbon futures. *Scientific Reports,* 5(1), 16518. *https://doi.org/10.1038/srep16518*

West, A. M., Kumar, S., & Jarnevich, C. S. (2016). Regional modeling of large wildfires under current and potential future climates in Colorado and Wyoming, USA. *Climatic Change,* 134(4), 565–577. *https://doi.org/10.1007/s10584-015-1553-5*

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase Western U.S. forest wildfire activity. *Science,* 313(5789), 940–943. *https://doi.org/10.1126/science.1128834*

Western Wood Products Association. (2000). Statistical Yearbook of the Western Lumber Industry. Western Wood Products Association, Economic Services Dept. *https://www.wwpa.org/resources/statistical-reports*

Westfall, J. A., Coulston, J. W., Gray, A. N., Shaw, J. D., Radtke, P. J., Walker, D. M., Weiskittel, A. R., MacFarlane, D. W., Affleck, D. L. R., Zhao, D., Temesgen, H., Poudel, K. P., Frank, J. M., Prisley, S. P., Wang, Y., Meador, A. J. S., Auty, D., & Domke, G. M. (2023). A national-scale tree volume, biomass, and carbon modeling system for the United States. U.S. Department of Agriculture, Forest Service. *https://www.fs.usda.gov/research/treesearch/66998*

Woolman, A. M., Coop, J. D., Shaw, J. D., & DeMarco, J. (2022). Extent of recent fire-induced losses of ponderosa pine forests of Arizona and New Mexico, USA. *Forest Ecology and Management, 520,* 120381. *https://doi.org/10.1016/j.foreco.2022.120381*

Worrall, J. J., Keck, A. G., & Marchetti, S. B. (2015). Populus tremuloides stands continue to deteriorate after drought-incited sudden aspen decline. *Canadian Journal of Forest Research,* 45(12), 1768–1774. *https://doi.org/10.1139/cjfr-2015-0225*

APPENDICES

Appendix A. Colorado Forest Carbon Inventories Review

Several significant reports and publications offer estimates of carbon inventories or emissions for Colorado. Below is a review of these documents and a brief discussion on the similarities and differences among these estimates. Our analysis is focused on documents that provide statewide estimates and include carbon pools similar to those presented in this report. We highlight data from the most recent year provided by these reports.

Appendix Table 1. *Similarities and differences among the methods and results of other statewide forest carbon inventory publications.*

REPORT NAME	DATA SOURCE(S)[2]	REPORTING YEAR	FLUX CALCULATION METHOD	CARBON POOLS INCLUDED	FOREST LAND CHANGE CATEGORY	STOCK (TGC)	FLUX (TGC YR-1)[5]
National GHG Inventory Dataset 1990 to 2021 [1]	NRI, FIA and the NLCD	2021 fluxes and 2022 stocks	IPPC's stock-difference method (available data) and model from Wear and Coulston (2015) and Coulston et al. (2015)'s framework	Aboveground biomass, belowground biomass, dead wood, litter, soil organic carbon	Forest land remaining forest land	1258.47	-3.25 ± 8.52[6]
					Forest land converted to nonforest	Not provided	-0.46
					Nonforest converted to forest land	Not provided	0.26
Colorado 2023 GHG Inventory [1]	NGHGI (Walters dataset)	2020	IPPC's stock-difference method with NGHGI data (Walters) and includes non-CO_2 emissions (CH4 and N20) from forest fires in the CO_2e flux	Aboveground biomass, belowground biomass, dead wood, litter, mineral soils	Forest land remaining forest land	Not provided	-3.14
					Other land converted to forest land	Not provided	0.27
Hoover and Smith, 2021 [1]	FIA DataMart accessed June 2020	Before June 2020, possibly 2017 [3]	Difference between remeasured forested plots	Aboveground live tree	Forest land remaining forest land	276.56 [4]	-4.13 [4]

1) Other statewide forest carbon inventory publications include "Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990 to 2021: Estimates and quantitative uncertainty for individual states, regional ownership groups, and National Forest System regions" (National GHG Inventory Dataset 1990 to 2021; Walters et al., 2023), "2023 Colorado Statewide Inventory of Greenhouse Gas Emissions and Sinks" (Colorado 2023 GHG Inventory; Twyman et al., 2023), and "Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States" (Hoover and Smith 2021). These publications use the FIA definition for tree area and cover requirements. If an area is surrounded by urban or developed lands, it is classified as settlements rather than forest land in the National GHG Inventory and 2023 Colorado GHG Inventory.

2) Data sources include the National Resources Inventory (NRI), National Land Cover Dataset (NLCD), and Forest Inventory and Analysis (FIA).

3) Hoover and Smith 2021 did not state the reporting year. It did state that the FIA database was accessed in June 2020. The NGHGI released in the same year reported FIA data in Colorado was available up to 2017.

4) Hoover and Smith 2021 provided estimates broken up by forest type (hardwoods, softwoods, and woodlands) and these were added together to provide one estimate in the table.

5) Each publication designated negative values to indicate a net carbon uptake; we switched this to negative values indicate an emission to be consistent with this report's results.

6) The range (i.e., ±) represents a 95% confidence interval.

US National Greenhouse Gas Inventory and Associated Publications

The EPA publishes the NGHGI, documenting GHG emissions and sinks from various sources and sectors since 1990, which aligns with the United Nations Framework Convention on Climate Change guidelines. This detailed record covers human induced GHG emissions and carbon sequestration from land management and land use changes (U.S. EPA, 2023b). Complementing this, the USDA's Northern Research Station releases an annual bulletin focusing on GHG emissions and removals related to forest land, woodlands, urban trees, and harvested wood products in the U.S., providing insights at the regional, state, and ownership levels based on the NGHGI data (Domke et al., 2023). The associated dataset is also released annually, providing tabular estimates and uncertainty estimates disaggregated by state (Walters et al., 2023).

The core dataset for forest carbon used is the FIA program and the methods follow the LULUCF chapter of the U.S. EPA (2023a, 2023b). The 2023 NGHGI provides estimates of forest ecosystem carbon stocks and net annual carbon stock change estimates derived from the IPCC's stock-difference methodology. Forested ecosystem carbon pools included in these inventories are aboveground biomass, belowground biomass, dead wood, litter, and soil organic carbon. Estimates of net flux and emissions are available up to 2021 and estimates of carbon stocks and land areas are provided through 2022. In Colorado, only FIA field data measured from 2002 to 2009 and remeasured again in 2012-2019 were available for analysis (U.S. EPA, 2023a, 2023b; Walters et al., 2023). For the years in which field data is unavailable for analyses, the authors produced a model following the framework of Wear & Coulston (2015). The model incorporates forest dynamics (age transition matrices) and land-use dynamics (land area transition matrices). More information is available in the NGHGI Annex 3.13 (U.S. EPA, 2023a).

The NGHGI report and Domke et al. (2023) include estimates of harvested wood products carbon for products in use and in solid waste disposal sites, aggregated at the national level. These estimates are based on data from the U.S. Census and USDA Forest Service surveys of production and trade and other sources. They use the WOODCARB II model for calculations and apply the IPCC's harvested wood products production approach (U.S. EPA, 2023b, 2023a). These harvested wood products estimates are not disaggregated at the state level.

The latest report and dataset covering Colorado provides annual stock and flux data spanning from 1990-2021 and estimates that from 2020-2021 the state is a net source of carbon from all LULUCF categories (-3.45 TgC yr^{-1}), of which forest land remaining forest land contributes -3.25 TgC yr^{-1} (U.S. EPA, 2023b; Walters et al., 2023). These estimates include aboveground biomass, belowground biomass, dead wood, litter, and organic soil. Carbon sequestration in Colorado from nonforest land converted to forest land was 0.26 TgC yr^{-1} where forest land converted to nonforest land emitted -0.46 TgC yr^{-1} (Walters et al., 2023).

Relative to all other states, Colorado is one of only about a dozen states that are net sources of carbon for forest land remaining forest land. However, Colorado also has one of the largest uncertainty ranges around this estimate with the 95% confidence interval ranging from 5.28 TgC yr^{-1} (a net sink) to -11.77 TgC yr^{-1} (a net source; Walters et al., 2023). Methane (CH_4) and nitrous oxide (N_20) emissions from forest fires and converted to $TgCO_2e$ are -0.28 $TgCO_2e$ yr^{-1} and -0.14 $TgCO_2e$ yr^{-1}, respectively, as provided in Walters et al. (2023).

Colorado Biennial Greenhouse Gas Inventory

In accordance with Senate Bill 19-096, the CDPHE is obligated to provide a statewide GHG inventory every two years. The CDPHE published the first inventory in 2019 and in 2021 released the Colorado GHG Inventory Update to meet this directive. The 2021 report summarizes the state's estimated GHG emissions and sinks from 2005 to 2018, with five-year interval projections from 2020 to 2050 (Taylor, 2021). This report covers multiple sectors including LULUCF. The 2021 Colorado GHG Inventory Update relies upon the US EPA SIT for the LULUCF module, which considers the balance between GHG emissions and carbon flux.

Within the LULUCF module, the SIT calculates forest carbon flux among five forest ecosystem pools: aboveground biomass, belowground biomass, dead wood, litter, and soil. Estimates for one harvested wood products pool is provided: wood products and landfills (combined). The report does not provide estimates of forest stocks or associated errors. Default EPA data collected from USDA Forest Service sources were used in the 2021 Colorado GHG Inventory Update to estimate emission and sequestration rates. The number of annual acres burned from wildfires in Colorado was specified with state-specific data from the National Interagency Fire Center (Taylor, 2021).

The 2021 report estimated the state's natural and working lands to comprise approximately 15% of Colorado's net GHG emissions as of 2018/2019. The LULUCF sector comprised

7% of net emissions, which includes the pools listed above but also includes many others including CO_2 emissions from forest fires, yard trimmings, food scraps, and agricultural soil carbon flux. In forests, aboveground biomass, belowground biomass, and litter were carbon sources in 2018 while dead wood, mineral soil, and total wood products and landfills were carbon sinks. Collectively, Colorado's forest carbon flux in 2018 was -2.76 TgC yr^{-1} (total wood products and landfills included) (Taylor, 2021).

CDPHE released an update in 2023, which cites the NGHGI data and divides emissions between two categories: forest land remaining forestland and land converted to forest land. Within both categories, the report estimates Colorado's forests as a net source of carbon, -2.87 TgC yr^{-1} in 2020 (Twyman et al., 2023). The report also provides non-CO_2 wildfire emissions of CH_4 (-0.995 $TgCO_2e$ yr^{-1}) and N_20 (-0.722 $TgCO_2e$ yr^{-1}) for 2020, applying a unique scale factor for each year that was based on the ratios of areas between several burned area datasets (Twyman et al., 2023). This is the only existing report that estimates emissions from the 2020 fire season at this time.

Hoover and Smith, 2021

A journal article by Hoover and Smith (2021) published in Carbon Balance Management titled 'Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States' provides state level estimates of carbon stocks and flux for the live tree aboveground carbon pool. The authors use FIA remeasurement data downloaded in June 2020. This is the only publication we found that uses remeasured plot data and provides estimates among vegetation categories. According to the NGHGI published the same year, the available remeasured Colorado FIA data was from 2002 to 2007 and 2012 to 2017 (U.S. EPA, 2020a, 2020b; Walters et al., 2021). Woodland vegetation in this report refers to pinyon/juniper and woodland hardwood forest types, which differs from how the NGHGI refers to woodlands. They estimated Colorado to be a net source of emissions (-4.28 TgC yr^{-1}) after combining hardwood forest emissions (-1.10 TgC yr^{-1}), softwood forest emissions (-3.08 TgC yr^{-1}) and woodland emissions (0.04 TgC yr^{-1}). They estimated the total carbon stock in forests to be 276.56 TgC (52.1 TgC in hardwoods, 174.5 TgC in softwoods, and 49.9 TgC in woodlands). They do not provide error estimates (Hoover & Smith, 2021).

Hiking to an FIA plot in the East Troublesome burn area. ***Photo: Christopher Tsz Hin Choi***

Appendix B. Harvested Wood Products Model Inputs & Results

Harvested Wood Products Data Sources

Western Wood Products Association (WWPA) Statistical Yearbooks are the oldest running data source we used, with data beginning in 1954 (Figure 4, Appendix Table 2). These WWPA reports provide intermittent annual total harvests from 1954 to 1967 across NFS, state/local, and private ownerships but did not provide disaggregated totals among each ownership. See Appendix Table 2 for our approach to fill in the missing years. WWPA was the main data source for NFS, State/Local, and private pre-2000. The only estimates available for Native American land from WWPA were from 1982 to 1991. Native American land was combined with private ownership to be consistent with the FIA ownership groupings.

State/local and private harvest data for 2002 to 2022 was taken from the USFS Four Corners Reports. These reports were released in 2002, 2007, 20212, and 2016 with estimates only available for those years. Harvests occurring on state land in 1999 to 2001 were obtained from internal CSFS archives. The Other Federal ownership category consists of only BLM harvest data. The BLM is the only other federal agency that programmatically engages in timber sales. This category was left as Other Federal to be consistent with the FIA ownership groupings. Our data sources did not provide BLM harvest estimates for 1996 and 2008, and we left these years as zeros.

Appendix Table 2. *Strategies for addressing data gaps in HWP data by ownership category and dataset.*

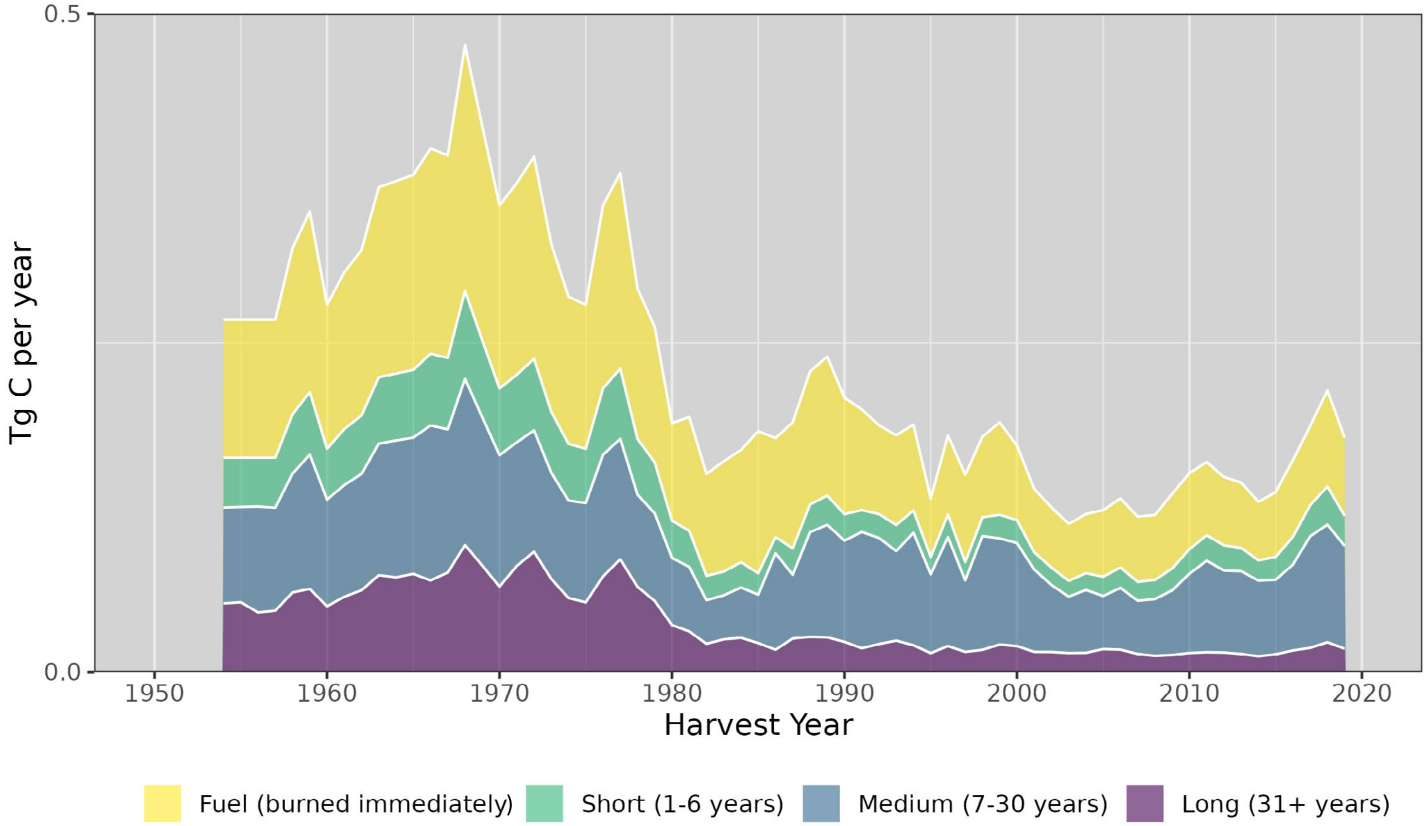
OWNERSHIP(S)	DATASET	MISSING YEAR(S)	FILL STRATEGY
Total across NFS, state/local, and private	WWPA	1955 to 1957	Filled with the total reported for 1954
Total across NFS, state/local, and private	WWPA	1964	The average of the total from 1963 and 1965
NFS, private, and state/local government	WWPA	1954 to 1967	We used the 10-year period from 1968 to 1977 to calculate annual ownership ratios. Then, we computed the average ratio for each ownership category over this period. These average ratios were then applied to the yearly totals for the years 1954 to 1967.
Private	WWPA & Four Corners Report	2001	The average from 2000 (from WWPA) and 2002 (Four Corners Report)
Private and state/local government	Four Corners Report	2003 to 2006	Filled with the reported amount in 2002
Private and state/local government	Four Corners Report	2008 to 2011	Filled with the reported amount in 2007
Private and state/local government	Four Corners Report	2013 to 2015	Filled with the reported amount in 2012
Private and state/local government	Four Corners Report	2017 to 2022	Filled with the reported amount in 2016

Timber Product Ratios

The USFS Cut and Sold Reports were the main data source for populating Timber Product Ratios. We aligned information in the Cut and Sold Reports with the model worksheet template in the following ways. For material without a hardwood or softwood designation such as green biomass (listed as "gnbiocv_biom"), this category was combined with softwood due to the predominant ratio of softwood to hardwood in other products. To maintain consistency in volume tracking, materials labeled as dead were also allocated to softwood categories. Specific categories of dead material included sawtimber, poles, fuelwood, nonsaw, misc, and drybiocv. Softwood excelsior was reported in the USFS Cut and Sold Reports but did not have a corresponding category in the template and was placed in softwood miscellaneous convertible. Categories in which there were no ratios for both hardwood and softwood products were retained in the model with zeros.

Product Lifespan Results

Primary products are distributed to various end-uses such as lumber in single family homes or lumber in packaging and shipping materials. Each end use has a different functional lifespan, which determines the amount and rate at which harvested wood products are retired from the PIU pool. Appendix Figure 1 shows the annual allocation of harvested carbon to instant oxidation or short (1 to 6 years), medium (7-30 years), and long-term (31+ years) end uses.



Appendix Figure 1. *Annual allocation of harvested carbon to instant oxidation or short, medium, and long-lived end-uses.*

Appendix C. Forest Ecosystem Carbon Results

Appendix Table 3. *Statewide carbon pool stock for forested lands from FIA plots measured between 2010 and 2019 and the "re-measurement stock" for forested lands remaining forested measured between 2012 and 2019. The 2010 to 2019 stock and 2012 to 2019 re-measurement stock based on just GRM plots differ by about 3% with the re-measurement stocks having a larger standard error due to fewer plots being used in the stock calculations. The re-measurement stock is only reported with disturbance results (see Section 4.1 for details). This table shows how the stocks by pool between the two stock estimates compare.*

	Stock		Re-measurement stock	
	Total	**SE**	**Total**	**SE**
	TgC		*TgC*	
Aboveground live	311.617	4.045	313.336	4.615
Aboveground dead	67.015	1.959	68.012	2.253
Belowground live	53.728	0.689	53.766	0.784
Belowground dead	14.293	0.409	14.509	0.470
Down woody material	62.320	1.124	62.047	1.290
Litter	96.316	0.840	101.085	0.926
Aboveground understory	22.064	0.239	20.721	0.278
Belowground understory	2.452	0.027	2.302	0.031
Soil	922.792	7.855	964.207	9.011
Total	1,552.597	12.006	1,599.986	13.735

Appendix Table 4. *Average annual net flux by disturbance, pool, and ownership. Fluxes are calculated for forest lands remaining forested for plots measured between 2002 to 2009 and 2012 to 2019.*

	Ownership group									
	US Forest Service		**Other federal**		**State and local government**		**Private**		**All ownerships**	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
	$TgC\ yr^{-1}$									
Cut										
Aboveground live	-0.171	0.060	-0.023	0.019	-0.012	-0.012	-0.041	0.026	-0.246	0.068
Growth	*0.053*	*0.013*	*0.002*	*0.002*	*0.007*	*0.004*	*0.034*	*0.010*	*0.096*	*0.017*
Removal	*-0.150*	*0.041*	*-0.023*	*0.018*	*-0.011*	*0.007*	*-0.064*	*0.027*	*-0.248*	*0.053*
Mortality	*-0.074*	*0.035*	*-0.002*	*0.002*	*-0.008*	*0.007*	*-0.010*	*0.005*	*-0.094*	*0.036*
Aboveground dead	-0.069	0.048	0.001	0.001	-0.011	0.010	-0.006	0.006	-0.085	0.049
Belowground live	-0.031	0.011	-0.004	0.003	-0.002	0.001	-0.007	0.004	-0.044	0.013
Belowground dead	-0.014	0.010	<0.001	<0.001	-0.002	0.002	-0.001	0.001	-0.017	0.010
Down woody material	<0.001	<0.001	-*	-*	-*	-*	-0.009	0.008	-0.009	0.008
Litter	-0.015	0.005	-0.005	0.004	-0.001	0.001	-0.002	0.004	-0.024	0.008
Aboveground understory	0.005	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.009	0.003
Belowground understory	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001
Soil	0.014	0.007	-0.002	0.002	-0.001	0.001	-0.001	0.004	0.011	0.008
Total without down woody material	-0.280	0.096	-0.031	0.026	-0.028	0.021	-0.056	0.033	-0.395	0.106
Total	-1.443	-	-0.080	-	-0.098	-	-0.345	-	-1.967	-
Fire										
Aboveground live	-0.332	0.080	-0.065	0.025	-0.014	0.013	-0.058	0.021	-0.470	0.087
Growth	*0.053*	*0.011*	*0.009*	*0.005*	*0.005*	*0.003*	*0.012*	*0.004*	*0.079*	*0.013*
Removal	*-**	*-**	*-**	*-**	*-**	*-**	*>-0.001*	*<0.001*	*>-0.001*	*<0.001*
Mortality	*-0.385*	*0.088*	*-0.074*	*0.030*	*-0.019*	*0.015*	*-0.070*	*0.024*	*-0.548*	*0.098*
Aboveground dead	0.071	0.038	0.008	0.011	0.004	0.004	0.007	0.007	0.090	0.040
Belowground live	-0.056	0.013	-0.015	0.005	-0.003	0.002	-0.013	0.005	-0.086	0.015
Belowground dead	0.019	0.008	0.002	0.002	0.001	0.001	0.001	0.001	0.023	0.008
Down woody material	-0.015	0.038	-*	-*	-*	-*	-*	-*	-0.015	0.038
Litter	-0.050	0.013	-0.011	0.004	-0.002	0.002	-0.006	0.002	-0.069	0.014
Aboveground understory	0.014	0.004	0.004	0.002	0.001	0.001	0.004	0.001	0.023	0.004
Belowground understory	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	<0.001
Soil	-0.038	0.014	-0.003	0.005	-0.001	0.001	-0.006	0.003	-0.048	0.015
Total without down woody debris	-0.371	0.091	-0.080	0.029	-0.014	0.012	-0.070	0.026	-0.535	0.100
Total	-0.386	-	-0.080	-	-0.014	-	-0.070	-	-0.550	-

	Ownership group									
	US Forest Service		Other federal		State and local government		Private		All ownerships	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
					TgC yr⁻¹					
Cut and fire										
Aboveground live	-0.001	0.001	-*	-*	-*	-*	0.001	0.001	<0.001	0.002
Growth	*<0.001*	*0.001*	-*	-*	-*	-*	*0.002*	*0.002*	*0.002*	*0.002*
Removal	*-0.002*	*0.002*	-*	-*	-*	-*	*>-0.001*	*<0.001*	*-0.002*	*0.002*
Mortality	*>-0.001*	*<0.001*	-*	-*	-*	-*	-*	-*	*>-0.001*	*<0.001*
Aboveground dead	<0.001	<0.001	-*	-*	-*	-*	-*	-*	<0.001	<0.001
Belowground live	>-0.001	<0.001	-*	-*	-*	-*	<0.001	<0.001	>-0.001	<0.001
Belowground dead	<0.001	<0.001	-*	-*	-*	-*	-*	-*	<0.001	<0.001
Down woody material	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*
Litter	>-0.001	0.001	-*	-*	-*	-*	>-0.001	<0.001	-0.001	0.001
Aboveground understory	>-0.001	<0.001	-*	-*	-*	-*	<0.001	<0.001	>-0.001	<0.001
Belowground understory	>-0.001	<0.001	-*	-*	-*	-*	<0.001	<0.001	>-0.001	<0.001
Soil	-0.001	0.001	-*	-*	-*	-*	-*	-*	-0.001	0.001
Total without down woody debris	-0.003	0.003	-*	-*	-*	-*	0.001	0.001	-0.002	0.004
Total	-0.003	-	0.000	-	0.000	-	0.001	-	-0.002	-
Insect and disease										
Aboveground live	-3.352	0.222	-0.368	0.087	-0.069	0.028	-0.229	0.059	-4.018	0.240
Growth	*1.497*	*0.060*	*0.146*	*0.020*	*0.048*	*0.013*	*0.252*	*0.025*	*1.943*	*0.065*
Removal	*-0.017*	*0.010*	-*	-*	*>-0.001*	*<0.001*	*-0.005*	*0.002*	*-0.022*	*0.010*
Mortality	*-4.833*	*0.250*	*-0.514*	*0.099*	*-0.117*	*0.036*	*-0.476*	*0.071*	*-5.939*	*0.268*
Aboveground dead	2.329	0.163	0.272	0.069	0.043	0.019	0.096	0.043	2.740	0.178
Belowground live	-0.574	0.038	-0.078	0.015	-0.014	0.005	-0.045	0.009	-0.711	0.041
Belowground dead	0.474	0.033	0.056	0.014	0.010	0.004	0.021	0.008	0.561	0.036
Down woody material	0.582	0.239	0.162	0.162	0.003	0.003	-0.034	0.067	0.713	0.296
Litter	-0.330	0.024	-0.035	0.010	-0.008	0.004	-0.020	0.007	-0.392	0.027
Aboveground understory	0.058	0.007	0.005	0.002	0.001	0.001	0.005	0.003	0.069	0.008
Belowground understory	0.006	0.001	0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.008	0.001
Soil	0.041	0.030	0.016	0.008	-0.004	0.013	-0.001	0.011	0.052	0.035
Total without down woody debris	-1.347	0.124	-0.132	0.037	-0.040	0.022	-0.171	0.050	-1.690	0.139
Total	-0.766	-	0.030	-	-0.037	-	-0.205	-	-0.977	-

	Ownership group									
	US Forest Service		Other federal		State and local government		Private		All ownerships	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	TgC yr^{-1}									
Natural										
Aboveground live	>-0.001	0.006	0.001	0.001	-0.005	0.004	-0.005	0.008	-0.008	0.011
Growth	*0.017*	*0.007*	*0.002*	*0.001*	*0.001*	*0.001*	*0.011*	*0.006*	*0.032*	*0.010*
Removal	-*	-*	-*	-*	-*	-*	*-0.004*	*0.004*	*-0.004*	*0.004*
Mortality	*-0.017*	*0.007*	*-0.001*	*0.001*	*-0.006*	*0.005*	*-0.013*	*0.008*	*-0.036*	*0.012*
Aboveground dead	-0.011	0.009	>-0.001	<0.001	<0.001	<0.001	-0.003	0.004	-0.014	0.010
Belowground live	>-0.001	0.001	-0.001	0.001	-0.001	0.001	-0.002	0.002	-0.003	0.002
Belowground dead	-0.002	0.002	>-0.001	<0.001	<0.001	<0.001	-0.001	0.001	-0.002	0.002
Down woody material	-*	-*	-*	-*	-0.015	0.015	0.006	0.006	-0.009	0.016
Litter	-0.002	0.001	<0.001	0.001	>-0.001	<0.001	0.002	0.002	<0.001	0.002
Aboveground understory	<0.001	<0.001	>-0.001	<0.001	<0.001	<0.001	-0.002	0.001	-0.001	0.001
Belowground understory	<0.001	<0.001	>-0.001	<0.001	<0.001	<0.001	>-0.001	<0.001	>-0.001	<0.001
Soil	0.006	0.006	-*	-*	-*	-*	-0.003	0.007	0.003	0.009
Total without down woody debris	-0.009	0.011	<0.001	0.001	-0.005	0.005	-0.012	0.017	-0.026	0.021
Total	-0.009	-	0.000	-	-0.020	-	-0.006	-	-0.035	-
All disturbed										
Aboveground live	-3.856	0.240	-0.454	0.092	-0.100	0.032	-0.332	0.068	-4.742	0.260
Growth	*1.620*	*0.061*	*0.161*	*0.021*	*0.061*	*0.014*	*0.311*	*0.027*	*2.152*	*0.067*
Removal	*-0.168*	*0.045*	*-0.023*	*0.018*	*-0.012*	*0.007*	*-0.073*	*0.027*	*-0.275*	*0.056*
Mortality	*-5.308*	*0.262*	*-0.592*	*0.103*	*-0.149*	*0.040*	*-0.569*	*0.075*	*-6.618*	*0.282*
Aboveground dead	2.320	0.174	0.280	0.069	0.037	0.022	0.094	0.044	2.732	0.189
Belowground live	-0.662	0.041	-0.098	0.016	-0.019	0.006	-0.066	0.012	-0.845	0.045
Belowground dead	0.477	0.035	0.057	0.014	0.009	0.005	0.021	0.008	0.564	0.038
Down woody material	0.818	0.063	0.070	0.019	0.021	0.007	0.099	0.019	1.008	0.068
Litter	-0.397	0.028	-0.050	0.011	-0.011	0.004	-0.026	0.009	-0.485	0.031
Aboveground understory	0.077	0.008	0.011	0.003	0.003	0.002	0.008	0.004	0.100	0.010
Belowground understory	0.009	0.001	0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.011	0.001
Soil	0.022	0.034	0.011	0.010	-0.006	0.013	-0.009	0.014	0.018	0.040
Total without down woody debris	-2.010	0.179	-0.242	0.053	-0.087	0.033	-0.308	0.067	-2.647	0.200
Total	-1.443	-	-0.080	-	-0.098	-	-0.345	-	-1.967	-

	Ownership group									
	US Forest Service		Other federal		State and local government		Private		All ownerships	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	TgC yr⁻¹									
Undisturbed										
Aboveground live	0.415	0.086	0.189	0.023	0.049	0.016	0.266	0.036	0.918	0.097
Growth	*1.815*	*0.070*	*0.371*	*0.022*	*0.100*	*0.017*	*0.599*	*0.035*	*2.883*	*0.077*
Removal	*-0.025*	*0.008*	*-0.002*	*0.001*	*-0.001*	*0.001*	*-0.073*	*0.025*	*-0.101*	*0.026*
Mortality	*-1.375*	*0.094*	*-0.180*	*0.025*	*-0.050*	*0.016*	*-0.259*	*0.029*	*-1.865*	*0.101*
Aboveground dead	0.018	0.057	-0.032	0.027	-0.011	0.014	-0.042	0.014	-0.067	0.065
Belowground live	0.045	0.015	-0.122	0.008	-0.001	0.003	-0.033	0.008	-0.111	0.019
Belowground dead	0.016	0.012	-0.004	0.005	-0.003	0.003	-0.007	0.003	0.002	0.014
Down woody material	0.338	0.290	0.008	0.090	0.004	0.018	-0.035	0.049	0.315	0.308
Litter	0.018	0.011	0.006	0.005	0.006	0.003	0.019	0.007	0.049	0.014
Aboveground understory	-0.008	0.004	-0.004	0.002	-0.000	0.001	-0.010	0.003	-0.022	0.006
Belowground understory	-0.001	0.000	-0.000	0.000	-0.000	0.000	-0.001	0.000	-0.002	0.001
Soil	-0.007	0.020	0.009	0.011	0.009	0.007	0.007	0.012	0.018	0.026
Total without down woody debris	0.496	0.100	0.042	0.036	0.048	0.022	0.198	0.047	0.785	0.117
Total	0.835	-	0.050	-	0.052	-	0.162	-	1.100	-

** Estimates are not reported for less than 500 acres.*

Appendix Table 5. *Carbon stock, average annual net carbon flux (excluding downed woody material), area, and carbon density for FIA forest types.*

	Stock		Flux *		Area		Carbon density	
	Total	SE	Total	SE	Total	SE	Total	SE
	TgC		*TgC yr^{-1}*		*Kha*		*Mg C ha^{-1}*	
Douglas-fir	107.484	6.560	-0.004	0.048	613.745	35.422	175.128	2.539
Pinyon/juniper woodland	237.173	7.065	-0.084	0.026	1,912.259	53.759	124.028	0.948
Deciduous oak woodland	141.993	6.587	0.065	0.030	1,016.587	44.373	139.676	1.527
Ponderosa pine	92.963	5.748	0.100	0.041	577.427	33.567	160.994	2.459
Aspen	268.310	10.419	-0.586	0.113	1,404.885	50.780	190.983	2.305
Engelmann spruce	181.713	9.900	-0.091	0.075	766.763	39.272	236.987	3.936
Subalpine fir	46.151	5.077	-0.150	0.054	203.839	20.796	226.408	6.635
Engelmann spruce/subalpine fir	194.052	10.034	-0.229	0.110	790.482	39.431	245.485	3.003
Juniper woodland	48.847	3.425	-0.008	0.010	480.837	31.207	101.588	1.792
Lodgepole pine	109.696	6.550	-0.284	0.070	572.348	32.789	191.659	2.860
White fir	18.314	3.146	-0.025	0.022	89.726	14.660	204.115	9.801
Cottonwood	6.043	1.521	-0.013	0.025	38.284	9.073	157.862	11.237
Rocky Mountain juniper	27.717	3.066	-0.003	0.013	214.714	22.297	129.090	3.318
Cercocarpus woodland	1.740	0.816	0.008	0.009	11.805	5.330	147.418	9.649
Foxtail pine/bristlecone pine	7.511	1.844	-0.017	0.014	43.160	9.468	174.028	12.873
Blue spruce	13.726	2.537	-0.010	0.023	72.013	12.593	190.609	8.334
Limber pine	11.010	2.247	-0.005	0.009	62.264	12.138	176.824	7.161
Southwestern white pine	0.645	0.522	>-0.001	<0.001	3.957	3.053	162.931	26.105
Cottonwood/willow	0.607	0.512	0.002	0.001	3.778	3.187	160.778	160.778
Sugarberry/hackberry/elm/green ash	0.335	0.230	0.005	0.005	3.396	1.978	98.568	25.358
Other exotic hardwoods	0.540	0.366	- **	- **	5.403	3.627	99.858	3.098
Non-stocked	36.027	3.346	-0.534	0.103	322.539	25.428	111.698	3.842
Total	1,552.597	12.006	-1.863	0.232	9,210.213	60.975	168.577	0.849

** Flux of the down woody material pool is not included in these fluxes.*

*** Estimates are not reported for less than 500 acres.*

Appendix Table 6. *Carbon stock by National Forest and pool from FIA plots measured between 2010 and 2019.*

	National forest																		All national forest	
	Arapaoe-Roosevelt		Grand Mesa-Uncompahgre-Gunnison		Manti-La Sal		Medicine Bow-Routt		Pawnee National Grassland		Pike and San Isabel		Rio Grande		San Juan		White River			
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	TgC																			
Aboveground live	19.378	1.175	49.913	2.236	0.257	0.140	17.309	1.272	-*	-*	29.761	1.476	18.729	1.142	34.322	1.661	35.590	1.899	205.259	3.993
Aboveground dead	9.020	0.749	7.495	0.678	0.008	0.008	8.818	0.752	-*	-*	2.781	0.280	9.430	0.983	9.333	0.958	7.215	0.626	54.101	1.878
Belowground live	2.990	0.180	8.335	0.379	0.051	0.028	2.740	0.207	-*	-*	4.788	0.238	2.987	0.184	6.060	0.301	5.827	0.315	33.778	0.670
Belowground dead	1.868	0.152	1.607	0.144	0.002	0.002	1.862	0.158	-*	-*	0.662	0.065	1.929	0.199	2.040	0.207	1.530	0.133	11.500	0.394
Down woody material	5.049	0.401	7.824	0.437	0.038	0.025	6.134	0.490	-*	-*	4.662	0.294	4.173	0.334	5.704	0.376	7.852	0.534	41.435	1.055
Litter	6.955	0.346	12.182	0.458	0.077	0.041	6.287	0.331	-*	-*	9.098	0.366	7.274	0.365	8.532	0.351	9.650	0.415	60.057	0.905
Aboveground understory	0.789	0.052	2.124	0.100	0.019	0.010	1.030	0.066	-*	-*	1.231	0.068	1.244	0.076	1.376	0.073	1.439	0.084	9.253	0.189
Belowground understory	0.088	0.006	0.236	0.011	0.002	0.001	0.114	0.007	-*	-*	0.137	0.008	0.138	0.008	0.153	0.008	0.160	0.009	1.028	0.021
Soil	53.149	2.481	95.743	3.728	0.976	0.510	48.244	2.526	-*	-*	66.626	2.629	55.768	2.832	64.774	2.587	77.963	3.490	463.243	7.134
Total	99.286	4.580	185.459	6.673	1.430	0.746	92.539	4.736	-*	-*	119.747	4.570	101.673	4.978	132.293	5.113	147.227	6.292	879.655	12.706

** Estimates are not reported for less than 500 acres.*

Appendix Table 7. *Average annual net carbon flux by National Forest and pool for forested lands remaining forested from FIA plots measured between 2002 to 2009 and 2012 to 2019. These fluxes do not include down woody material.*

	National forest																				
	Arapaoe-Roosevelt		**Grand Mesa-Uncompahgre-Gunnison**		**Manti-La Sal**		**Medicine Bow-Routt**		**Pawnee National Grassland**		**Pike and San Isabel**		**Rio Grande**		**San Juan**		**White River**		**All national forest**	
	Total	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**	**Total**	**SE**
									TgC yr^-1											
Aboveground live	-0.654	0.089	-0.303	0.093	0.004	0.003	-0.582	0.095	-***	-***	0.004	0.054	-1.031	0.140	-0.654	0.123	-0.225	0.084	-3.441	0.255
Growth	*0.375*	*0.025*	*0.713*	*0.036*	*0.005*	*0.003*	*0.417*	*0.030*	-***	-***	*0.396*	*0.024*	*0.363*	*0.023*	*0.500*	*0.030*	*0.665*	*0.040*	*3.435*	*0.075*
Removal	*-0.049*	*0.026*	*-0.012*	*0.005*	-	-	*-0.063*	*0.030*	-***	-***	*-0.024*	*0.009*	*-0.014*	*0.010*	*-0.003*	*0.003*	*-0.027*	*0.017*	*-0.193*	*0.046*
Mortality	*-0.979*	*0.094*	*-1.004*	*0.101*	*<-0.001*	*<0.001*	*-0.937*	*0.097*	-***	-***	*-0.368*	*0.055*	*-1.381*	*0.152*	*-1.151*	*0.129*	*-0.863*	*0.090*	*-6.683*	*0.264*
Aboveground dead	0.390	0.062	0.361	0.068	<-0.001	<0.001	0.180	0.069	-***	-***	-0.002	0.034	0.746	0.100	0.447	0.087	0.216	0.062	2.338	0.182
Belowground live	-0.110	0.015	-0.069	0.016	<-0.001	0.001	-0.102	0.017	-***	-***	-0.004	0.009	-0.172	0.023	-0.120	0.022	-0.039	0.014	-0.617	0.044
Belowground dead	0.086	0.012	0.074	0.014	<-0.001	<0.001	0.047	0.014	-***	-***	0.004	0.007	0.144	0.019	0.093	0.018	0.044	0.013	0.493	0.037
Down woody debris *	0.224	0.137	0.038	0.121	-	-	0.126	0.094	-***	-***	0.004	0.120	0.045	0.095	-0.041	0.095	0.508	0.260	0.905	0.373
Litter	-0.070	0.011	-0.037	0.011	0.001	<0.001	-0.049	0.010	-***	-***	-0.003	0.007	-0.144	0.018	-0.053	0.012	-0.025	0.008	-0.379	0.030
Aboveground understory	0.019	0.004	0.005	0.003	<-0.001	<0.001	0.012	0.003	-***	-***	0.002	0.003	0.024	0.005	0.004	0.004	0.003	0.003	0.069	0.009
Belowground understory	0.002	<0.001	0.001	<0.001	<-0.001	<0.001	0.001	<0.001	-***	-***	<0.001	<0.001	0.003	0.001	<0.001	<0.001	<0.001	<0.001	0.008	0.001
Soil	0.036	0.017	-0.037	0.012	<0.001	<0.001	0.065	0.018	-***	-***	-0.003	0.009	-0.036	0.020	-0.029	0.014	0.020	0.011	0.015	0.040
Total without down woody debris	-0.300	0.065	-0.006	0.062	0.004	0.003	-0.428	0.095	-***	-***	-0.001	0.058	-0.466	0.098	-0.311	0.080	-0.006	0.085	-1.514	0.206
Total **	-0.076	-	0.033	-	0.004	-	-0.302	-	-***	-***	0.003	-	-0.421	-	-0.352	-	0.503	-	-0.608	-

** Flux of the down woody material pool is calculated from a subset of plots*

*** Standard error not recorded for total with down woody material*

**** Estimates are not reported for less than 500 acres.*

Appendix Table 8. *Carbon stock by pool and forest type group from forested FIA plots measured between 2010 and 2019.*

	Aboveground live		Aboveground dead		Belowground live		Belowground dead		Down woody material		Litter		Aboveground understory		Belowground understory		Soil		Total	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
											TgC									
Pinyon / juniper group	41.823	1.227	3.097	0.182	8.874	0.266	0.744	0.045	9.520	0.399	15.795	0.412	6.472	0.144	0.719	0.016	226.694	5.560	313.738	7.583
Douglas-fir group	27.924	1.806	3.592	0.468	4.951	0.325	0.824	0.102	4.248	0.314	7.243	0.455	0.545	0.038	0.061	0.004	58.096	3.605	107.484	6.560
Ponderosa pine group	23.533	1.638	0.752	0.125	4.207	0.307	0.176	0.030	2.215	0.216	5.205	0.333	0.632	0.041	0.070	0.005	56.173	3.501	92.963	5.748
Fir/spruce/ mountain hemlock group	116.635	4.110	36.302	1.793	18.506	0.674	7.754	0.375	24.796	1.011	33.094	1.007	2.749	0.094	0.305	0.010	213.817	6.595	453.956	13.617
Lodgepole pine group	27.610	1.885	8.077	0.830	4.522	0.315	1.634	0.168	5.126	0.454	8.919	0.542	0.663	0.047	0.074	0.005	53.072	3.158	109.696	6.550
Other western softwood groups	3.861	0.658	0.813	0.243	0.597	0.101	0.181	0.049	0.844	0.149	1.328	0.208	0.181	0.027	0.020	0.003	11.339	1.756	19.166	2.927
Elm/ash/ cottonwood group	1.955	0.502	0.127	0.053	0.273	0.074	0.021	0.008	0.237	0.093	0.225	0.056	0.164	0.035	0.018	0.004	3.965	0.979	6.986	1.622
Aspen/birch group	58.511	2.838	10.562	0.703	9.502	0.462	2.137	0.143	11.257	0.548	16.623	0.684	5.118	0.186	0.569	0.021	154.031	6.029	268.310	10.419
Woodland hardwoods	9.316	0.589	0.888	0.193	2.230	0.131	0.194	0.045	2.211	0.175	6.407	0.305	4.287	0.187	0.476	0.021	117.722	5.491	143.733	6.636
Other exotic hardwoods	0.043	0.037	-*	-*	0.006	0.005	-*	-*	0.004	0.003	0.018	0.012	0.022	0.015	0.002	0.002	0.445	0.298	0.540	0.366
Nonstocked	0.407	0.070	2.805	0.595	0.059	0.010	0.628	0.130	1.863	0.282	1.458	0.146	1.232	0.097	0.137	0.011	27.438	2.504	36.027	3.346
Total	311.617	4.045	67.015	1.959	53.728	0.689	14.293	0.409	62.320	1.124	96.316	0.840	22.064	0.239	2.452	0.027	922.792	7.855	1,552.597	12.006

** Estimates are not reported for less than 500 acres.*

Appendix Table 9. *Average annual net carbon flux by pool and forest type group for forest lands remaining forested from FIA plots measured from 2002 to 2009 and 2012 to 2019.*

	Aboveground live								Aboveground dead		Belowground live		Belowground dead		Down woody material *		Litter		Aboveground understory		Belowground understory		Soil		Total flux without down woody material		Total **	
	Net flux		Growth		Removal		Mortality																					
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
															$TgC\ yr^{-1}$													
Pinyon / juniper group	0.184	0.020	0.414	0.016	-0.025	0.008	-0.205	0.017	-0.006	0.012	-0.232	0.010	>-0.001	0.003	0.077	0.117	-0.006	0.008	-0.008	0.003	>-0.001	<0.001	-0.026	0.012	-0.095	0.030	-0.019	-
Douglas-fir group	-0.125	0.067	0.394	0.031	-0.020	0.008	-0.499	0.078	0.146	0.046	-0.020	0.012	0.031	0.009	-0.083	0.050	-0.012	0.009	-0.011	0.003	>-0.001	<0.001	-0.012	0.010	-0.004	0.048	-0.087	-
Ponderosa pine group	0.124	0.031	0.292	0.025	-0.061	0.019	-0.108	0.021	-0.027	0.018	0.022	0.006	-0.005	0.004	0.030	0.099	0.011	0.004	-0.012	0.003	>-0.001	<0.001	-0.011	0.011	0.100	0.041	0.130	-
Fir/spruce/ mountain hemlock group	-2.130	0.216	1.907	0.072	-0.095	0.034	-3.942	0.236	1.657	0.163	-0.364	0.037	0.350	0.033	0.297	0.299	-0.152	0.021	0.019	0.005	0.002	0.001	0.114	0.027	-0.504	0.145	-0.207	-
Lodgepole pine group	-0.612	0.097	0.437	0.033	-0.055	0.027	-0.994	0.111	0.423	0.077	-0.102	0.016	0.090	0.015	0.403	0.224	-0.066	0.012	0.008	0.003	0.001	<0.001	-0.026	0.010	-0.284	0.070	0.119	-
Other western softwood groups	-0.048	0.031	0.037	0.008	--***	--***	-0.085	0.034	0.038	0.023	-0.008	0.005	0.007	0.004	0.097	0.074	-0.006	0.004	-0.001	0.001	>-0.001	<0.001	-0.004	0.004	-0.022	0.017	0.075	-
Elm/ash/ cottonwood group	0.009	0.012	0.036	0.011	-0.001	0.001	0.027	0.012	-0.014	0.014	<0.001	0.002	-0.002	0.002	-0.006	0.007	>-0.001	0.001	-0.000	0.000	>-0.001	<0.001	0.001	0.002	-0.006	0.026	-0.012	-
Aspen/birch group	-0.890	0.125	1.250	0.064	-0.061	0.023	-2.079	0.146	0.411	0.071	-0.157	0.020	0.084	0.014	0.209	0.094	-0.135	0.016	0.054	0.006	0.006	0.001	0.041	0.022	-0.586	0.113	-0.377	-
Woodland hardwoods	0.054	0.025	0.228	0.018	-0.007	0.003	-0.167	0.025	-0.007	0.017	-0.022	0.006	-0.001	0.003	-0.022	0.019	0.004	0.005	0.007	0.002	0.001	<0.001	0.038	0.013	0.073	0.032	0.051	-
Other exotic hardwoods	--***	--***	--***	--***	--	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	--***	-
Nonstocked	-0.390	0.094	0.041	0.009	-0.052	0.027	-0.380	0.097	0.044	0.059	-0.071	0.016	0.012	0.012	-0.007	0.021	-0.072	0.015	0.022	0.004	0.002	<0.001	-0.081	0.020	-0.534	0.103	-0.541	-
Total	-3.824	0.279	5.035	0.076	-0.377	0.062	-8.483	0.282	2.664	0.200	-0.956	0.048	0.567	0.040	0.995	0.425	-0.436	0.034	0.078	0.011	0.009	0.001	0.036	0.048	-1.863	0.232	-0.867	-

* *Flux of the down woody material pool is calculated from a subset of plots*

** *Standard error not recorded for total with down woody material*

*** *Estimates are not reported for less than 500 acres.*

SUPPLEMENTAL MATERIALS

The following supplemental materials provide detailed input data and results for the Harvested Wood Products Model. Spreadsheets for each are available to download at the links below.

Supplemental File S1

Harvested Wood Products Model Input Data available to download *here*.

This spreadsheet contains the input file for Groom Analytics' harvested wood products model, as adopted from Groom Analytics' Rocky Mountain region template. Default values were used for all tabs except Harvest_MBF, BFCF, and TimberProdRatios. The below explanations are from Groom and Tase, 2002.

- **Harvest_MBF:** Annual harvest values in thousand board feet (MBF) among four ownership groupings in Colorado. Ownership groupings include National Forest System (NFS), private and Native American, state and local, and other federal entities. The last column provides the total annual MBF. Sources: Western Wood Products Association yearbooks (2000), USDA Four Corner reports (2006, 2012, 2016, 2021), USFS Cut and Sold Reports (2022), and data from the Bureau of Land Management.
- **BFCF:** The BFCF tab contains the conversion factors between board feet and cubic feet for various time periods. Source: 2022 USFS Cut and Sold Reports and correspondence with K. Stockmann (2023).
- **TimberProdRatios:** This tab contains annual timber product ratios (TPR), which represent the portion of the annual harvest that is classified as specific timber products, such as sawtimber, fuelwood, poles, and posts. The first column, TimberProductID, is a numerical identifier of the timber product category name. Timber product category names are specified in the tab named RatioCategories. The remainder of the columns are named after the sequential years of harvest data, from the earliest year to the final year. Sources: USFS Cut and Sold Reports 1980 to 2008 and 2009 to 2019.
- **PrimaryProdRatios:** This tab contains the annual primary product ratios (PPR), which represent the portion of annual timber product that is used in specific primary products, such as fuelwood, wood pulp, plywood, and lumber. The first column, PrimaryProductID is a numerical identifier of the primary product category name. Primary product category names are specified in the tab named RatioCategories. The remainder of the columns are named after the sequential years of harvest data. Sources: Smith et al. (2006).
- **EndUseRatios:** This tab contains end use ratios (EUR), which determine the annual distribution of primary wood products (e.g., plywood, lumber) to end-uses such as single-family new housing and furniture manufacturing. Sources: Mckeever (2009) and Mckeever & Howard (2011).
- **RatioCategories:** This tab acts as a link between TPR, PPR, and EUR categories specified numerically in the TPR, PPR, and EUR tabs.
- **CCF_MT_Conversion:** This tab contains factors to convert CCF volumes of individual primary products to metric tons of carbon. Sources: Smith et al. (2006) and Skog (2008).
- **EU_HalfLives:** End-use product half-life values express the decay rate at which carbon in the products in use category passes into the Discarded Products category. National default values were used. Sources: Smith et al. (2006).
- **DiscardFates:** In any specified inventory year, wood and paper from all production years transition from the PIU pool to the discarded products category. Discarded products categories include discard energy capture, burned without energy capture, recovered, composted, landfills, and dumps. Sources: Skog (2008), Freed (2004), Melosi (1982) and Melosi (1991).
- **Discard_HalfLives:** Discarded products disposition half-lives are the half-lives of wood and paper, which vary between landfills, dumps, and recovered (recycled) products. These values determine the quantity and rate harvested wood products are emitted with and without energy capture at the end of their functional lifespan. Sources: Skog (2008).
- **MonteCarloValues**

Supplemental File S2

Harvested Wood Products Model Results available to download *here.*

This spreadsheet contains the following tabs of HWP results, as provided in Groom & Tase (2022):

- **Tab 1.0 Annual Harvest:** This table provides annual harvest (BBF), timber product output (TgC yr^{-1}), and cumulative timber product output (TgC yr^{-1}) from 1954 to 2019 for each ownership.
- **Tab 2.0 Harvest Halflives:** This table provides annual amount (TgC and $TgCO_2e$) and proportion of total (pct) of harvested timber destined for fates with different half-lives.
- **Tab 3.0 Cumulative Ownership Storage Emissions:** This table provides cumulative storage and emissions by ownership and pool in TgC.

- **Tab 3.5 Cumulative Ownership Storage Emissions CO_2e:** This provides the same information as Tab 3.0 but in TgCO_2e instead of TgC.
- **Tab 4.0 Cumulative Storage Emissions Summary:** This table provides the cumulative amount of carbon stored in PIU and SWDS pools and the cumulative amount of carbon emitted as EEC or EWOEC. The units are in TgC and TgCO_2e.
- **Tab 4.5 Cumulative Storage Emissions Detail:** This provides a detailed version of Tab 4.0 of cumulative values in TgC and TgCO_2e. It breaks out the overall PIU into PIU and Recovered, SWDS into a non-decaying portion of the landfill (Landfill_fixed), a decaying portion of the landfill (Landfill_available), and dumps. For emissions there is burned with energy capture (Fuelwood), emissions from dumps, landfills, and recovered products (DumpsEmit, LandfillEmit, RecoveredEmit), compost, and burned waste with and without energy capture (DiscardEnergyCapture, BurnNoCapture).
- **Tab 4.8 Cumulative Storage Emissions Halflives:** Columns in this table depict the amount of carbon (TgC, TgCO_2e) that resides in pools or has been cumulatively emitted from sources with different halflives. SWDS (swds), PIU (pu), and EWOEC (E) are broken into their half-life category components, short, medium, and long (st, md, lng). Since EEC (eec) represents fuel wood that was burned immediately, it has no half-life components.
- **Tab 5.0 Annual Storage Emissions Change:** Values are in TgC and TgCO_2e. We subtracted the value of one year's SWDS, PIU, EWOEC, and EEC values from the previous to determine what the annual change was. NetStockChange is the sum of the stock, or pool, values of SWDS and PIU. The column Harvest is in TgC and Harvest_CO_2 is in TgCO_2e. The value given for harvest is the harvest amount the year before the one listed under column Year. The harvest column also equals the sum of the changes in SWDS, PIU, EWOEC, and EEC.
- **Tab 6.0 MC Components Summary:** There are values for each year and pool/emission type (Column: Type.M) such as eec (Emitted with Energy Capture), ewoec (Emitted Without Energy Capture), swds (Solid Waste Disposal Sites) and pu (Products in Use). The figure is constructed using Means (yellow line), lci, and uci (lower and upper 90% confidence intervals). The Means are calculated by finding the mean value for an emission or pool type among iteration values for a given year. The columns lci and uci represent lower and upper 90% confidence intervals, derived directly from the distribution of iteration values for the pool or emissions type from a given years. The two columns pct_lci and pct_uci represent a percentage of the mean for the lower and upper confidence intervals. Pct_lci = lci / Means; pct_uci = uci / Means. The values in this table are cumulative MTC.
- **Tab 7.0 PIU Plus SWDS:** The values units are cumulative MTC which the Shiny application transforms to TgC and TgCO_2e. The column Mean represents the mean value of SWDS plus PIU values for a given year across iterations. The columns lci and uci represent lower and upper 90% confidence intervals, derived directly from the distribution of iteration values for given years.

OUR MISSION

TO ACHIEVE STEWARDSHIP OF COLORADO'S DIVERSE FOREST ENVIRONMENTS FOR THE BENEFIT OF PRESENT AND FUTURE GENERATIONS

COLORADO STATE FOREST SERVICE

5060 Campus Delivery
Fort Collins, CO 80523-5060
(970) 491-6303
csfs.colostated.edu

WARNER COLLEGE OF NATURAL RESOURCES
COLORADO STATE UNIVERSITY

1401 Campus Delivery
Fort Collins, CO 80523-1401
(970) 491-6675
warnercnr.colostate.edu

NATURAL RESOURCE ECOLOGY LABORATORY

1499 Campus Delivery
Fort Collins, CO 80523-1499
(970) 491-5571
www.nrel.colostate.edu